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**GENERATION IV NUCLEAR ENERGY SYSTEMS  
TEN YEAR PROGRAM PLAN**

*Fiscal Year 2004*



*February 27, 2004*

**Office of Advanced Nuclear Research  
DOE Office of Nuclear Energy, Science and Technology**

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**FINAL DRAFT**

## **Disclaimer**

The Generation IV Nuclear Energy Systems Ten Year Program Plan describes the plans that were in force at the start of calendar year 2004. However, the Generation IV research & development (R&D) plans will continue to evolve. Even as this Program Plan is being released, several system R&D plans are still under development, most in collaboration with international, university and industry partners. Consequently, the Program Plan should be viewed as a work in progress. For current information regarding this document or the plans described within, please contact:

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## Executive Summary

As reflected in the U.S. *National Energy Policy*,<sup>1</sup> nuclear energy has a strong role to play in satisfying our nation's future energy security and environmental quality needs. The desirable attributes of nuclear energy give it a cornerstone position, not only in the U.S. energy portfolio, but also in the world's future energy portfolio. Accordingly, on September 20, 2002, U.S. Energy Secretary Spencer Abraham announced that, "The United States and nine other countries have agreed to develop six Generation IV nuclear energy concepts."<sup>2</sup> The Secretary also noted that the systems are expected to "represent significant advances in economics, safety, reliability, proliferation-resistance, and waste minimization." The six systems and their broad research and development (R&D) needs are described in the *Generation IV Technology Roadmap*,<sup>3</sup> and the first ten years of required R&D to achieve the goals described in roadmap are outlined in this program plan.

### *Vision*

The *National Energy Policy* issued by the Bush Administration in May 2001 recommended an expansion of nuclear energy in this country, development of advanced nuclear fuel cycles and next generation technologies, and development of advanced reprocessing and fuel treatment technologies. Recent studies by the Massachusetts Institute of Technology (MIT)<sup>4</sup> and National Laboratory Directors<sup>5</sup> have also emphasized the need for growth in nuclear power. To achieve this vision, the U.S. must be a worldwide leader in the development and demonstration of technical options that are used to:

- 1) Expand the use of nuclear energy worldwide,
- 2) Effectively manage radioactive waste,
- 3) Reduce the threat of nuclear material misuse, and
- 4) Enhance national security.

The Office of Advanced Nuclear Research (DOE/NE-20) has adopted an integrated strategy consisting of the Generation IV Nuclear Energy Systems Initiative (Generation IV), the Nuclear Hydrogen Initiative (NHI), and the Advanced Fuel Cycle Initiative (AFCI).

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<sup>1</sup> "National Energy Policy," *National Energy Policy Development Group*, May 2001, available at <http://www.whitehouse.gov/energy/National-Energy-Policy.pdf>, accessed February 2004.

<sup>2</sup> *Nuclear News*, November, 2002, pp. 20–26.

<sup>3</sup> "A Technology Roadmap for Generation IV Nuclear Energy Systems," *Generation IV International Forum*, GIF-002-00, December 2002, available at <http://www.inel.gov/initiatives/generation.shtml>, accessed January 2004.

<sup>4</sup> "The Future of Nuclear Power," Interdisciplinary MIT Study, 2003, available at <http://web.mit.edu/nuclearpower/>, accessed February, 2004.

<sup>5</sup> See "Nuclear Energy: Power for the 21<sup>st</sup> Century—An Action Plan," Six DOE Lab Action Plan, April 30, 2003, Executive Summary at: <http://nuclear.inel.gov/papers-presentations/default.shtml>

## *Mission*

The Generation IV, NHI, and AFCI programs are working together to develop the next generation of nuclear energy systems capable of providing energy for generations of Americans, by:

- Developing and demonstrating advanced nuclear energy systems that meet future needs for safe, sustainable, environmentally responsible, economical, proliferation-resistant, and physically secure energy, and
- Developing and demonstrating technologies that enable the transition to a stable, long-term, environmentally, economically, and politically acceptable advanced fuel cycle

The Generation IV program supports these goals through its mission to develop innovative, next-generation reactor technologies. Within the Generation IV program, the Next Generation Nuclear Plant (NGNP) project is a major thrust to develop and demonstrate advanced high temperature reactor technology with the capability to power the economic production of hydrogen and electricity. The Generation IV program is also investing in the development of next-generation fast neutron spectrum reactor technologies that hold significant promise for advancing sustainability through improved economics and safety while reducing nuclear waste generation and the risk of proliferation. A new fleet based on the most successful Generation IV reactors will greatly enhance today's existing reactors and provide value to the nation.

Closely coupled to the Generation IV program is the Nuclear Hydrogen Initiative (NHI). This emerging program supports these goals by its mission to demonstrate hydrogen production technologies using nuclear energy. The initiative will develop hydrogen production technologies that are shown to be compatible with nuclear energy systems through scaled demonstrations. A commercial-scale demonstration plant could be coupled with a Generation IV demonstration facility by the middle of the next decade.

Achieving the DOE-NE vision will also require that the country transition from the current once through fuel cycle to an advanced fuel cycle. The Advanced Fuel Cycle Initiative (AFCI) is a broad R&D program whose mission is to develop and demonstrate technologies that enable the transition to an environmentally, socially, economically and politically acceptable advanced fuel cycle. The primary AFCI goals are to develop fuel systems for Generation IV reactors and create enabling fuel cycle technologies, including fuel, cladding, separations, fuel fabrication, waste forms, and disposal technology, to reduce spent fuel volume, separate long-lived, highly radiotoxic elements, and reclaim valuable energy from spent fuel. The AFCI technologies will support both current and future nuclear energy systems, including Generation IV systems. The AFCI is emphasizing the central role of systems analysis to define and assess the optimal deployment strategies, as well as the best possible transition from the current system to a future U.S. nuclear fuel cycle.

## ***Strategy***

As indicated above, several of the Generation IV systems are particularly well-suited to the U.S. national energy needs. A *Generation IV Implementation Strategy*<sup>6</sup> was developed by DOE NE in FY 2003 that focuses the program on two principal priorities:

### **Priority 1: *Develop a Next Generation Nuclear Plant (NGNP) to achieve economically competitive hydrogen and electricity production in the mid-term.***

The NGNP is presently based on the Generation IV Very High Temperature Reactor (VHTR) design, i.e., a prismatic- or pebble-bed, high-temperature gas-cooled reactor that is able to economically produce hydrogen and electricity. The high priority on developing a capability for nuclear-generated hydrogen with the NGNP reflects the excellent potential for this system to provide a major competitive advance toward the long-standing need to diversify the energy supply of the U.S. transportation sector, and to do this in a manner that is essentially emissions-free. Successful development and demonstration of an economically competitive, emissions-free nuclear-generated hydrogen supply will be the focus of a government-laboratory-industry-international collaboration to design, develop, construct and operate a NGNP that is dedicated to hydrogen production research and demonstration.

The NGNP program is projected to complete its key R&D by about 2012. This is partially enabled by many prior developments in high-temperature gas-cooled reactors internationally. As a result, completion and startup of a demonstration NGNP is targeted for 2016. The startup test program will include an extensive integral system safety test and demonstration phase that will form part of the safety basis for future U. S. Nuclear Regulatory Commission commercial licensing. The development of a NGNP would have a number of associated benefits including the establishment of a technical basis for development of a fast-spectrum gas reactor as discussed in the next section.

### **Priority 2: *Develop a fast reactor to achieve significant advances in sustainability for the long term.***

The priority on fast reactors reflects their excellent potential to make significant gains in reducing the volume and radiotoxicity, and increasing the manageability of spent nuclear fuel. With a successful fast reactor program, the U.S. may be able to avoid the need for a second geological repository for many decades. Fast reactors also hold the potential for extending the useful energy yield of the world's finite uranium supply many-fold, if needed in the very long term.

The chief issues in the development of a next-generation fast-spectrum reactor for use in the United States are its economic competitiveness and management of the overall risks to workers and the public from the deployment of a closed fuel cycle. The most promising fast-spectrum Generation IV systems are the Gas Fast Reactor (GFR), the Lead Fast Reactor (LFR), and the Sodium Fast Reactor (SFR). Among these, the LFR and GFR will be given the most emphasis in

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<sup>6</sup> "The U.S. Generation IV Implementation Strategy," U.S. Department of Energy, September, 2003, available at <http://nuclear.gov/geniv/gen-ivstrategy.html>, accessed January 2004.

order to resolve technical issues and uncertainties, since these reactors offer strong potential benefits that have not been fully demonstrated. The SFR is already at a fairly advanced state of development, with many of its technologies having been demonstrated internationally. All of these systems should be brought to a state where a downselection can be undertaken based on demonstrated performance of their economics, safety and reliability, sustainability, and proliferation resistance and physical protection. The Generation IV program gives the highest priority to advancing the LFR and GFR, while monitoring the progress of the SFR internationally.

### ***Advancing All of the Generation IV Systems***

The priorities identified in the Implementation Plan specify the direction of the major thrusts in the Generation IV program. However, the program also addresses those systems not in the forefront of U.S. development, but which have significant international interest in their potential. The roadmap identified six most promising systems, four of which are mentioned above. The additional two are the Supercritical-Water-Cooled Reactor (SCWR) and the Molten Salt Reactor (MSR). The SCWR employs water above the critical temperature and pressure that affords a considerable increase in thermal efficiency as well as major simplifications and savings in the balance of plant. The MSR employs a circulating liquid fuel mixture that offers considerable flexibility for recycling actinides, and may provide a favorable alternative to accelerator-driven systems. The Generation IV program includes significant international collaborative efforts on the SCWR, and exploratory collaborations on the MSR.

### ***Organization***

An organization for the Generation IV program has been created to advance the systems as well as the many R&D needs that are common to two or more of the systems. Thus, each of the six Generation IV systems has a System Integration Manager (SIM) that is responsible for ensuring the R&D is focused on the highest priority needs of their system. In addition, National Technical Directors (NTDs) are responsible for System Design & Evaluation Methods, Materials, and Energy Conversion who focus R&D resources on needs identified by two or more systems that benefit from a common focus. In this way R&D funds can be spent efficiently while the full scope of R&D requirements in each area can be addressed. The Generation IV program has a Technical Integrator to plan the development of tasks and schedules to ensure that all necessary R&D projects are being performed or planned for future investigation, and to ensure that the Generation IV R&D complements that of the Advanced Fuel Cycle Initiative. To be fully integrated, the AFCI and Generation IV R&D are overseen by a common Systems Analysis function that guides the development of system requirements and interfaces. The emerging NHI program is also being closely integrated, primarily with the NGNP project that will demonstrate its technologies first.

### ***Key Research & Development***

As described in the Generation IV Technology Roadmap, the R&D is expected to span as much as 30 years for some of the systems. The scope of R&D found in this 10-year plan are, of

necessity, more near- and mid-term. Within this limited span, the highest-priority R&D includes the following broad categories:

- *Thermal-spectrum fuels testing for the NGNP.* To meet the objectives of the NGNP program, fuel irradiation testing will be performed in the Advanced Test Reactor at INEEL. In-core test facilities will be developed to create the unique high-temperature environment needed for the fuel qualification.
- *Hydrogen production technology development, assessment, & demonstration for the NGNP.* A systematic evaluation of process potential for the sulfur-iodine hydrogen production technologies will be performed and a few demonstrated at engineering scale. These technologies require a rigorous economic evaluation to ensure hydrogen can be produced at a cost that is competitive with gasoline. A non-nuclear test bed is needed to ensure that the technologies are sufficiently developed and scaled-up for the subsequent nuclear demonstration with the NGNP system.
- *Certification of analysis tools to enable evaluation of the system behavior and licensing for the NGNP.* The analysis tools required to perform design and licensing calculations consist of thermal-hydraulics software, computational fluid dynamics (CFD) software, neutronics software, and mechanical assessment software.
- *Fast-spectrum fuels testing for the LFR and GFR.* The longer-term development needs of sustainable systems require fast-spectrum irradiation testing. Such capability does not now exist in the United States, and the limited capabilities in the world are in decline. Options for reversing this trend need to be developed and evaluated. A new fast neutron facility may need to be developed in the long term.
- *Materials selection & testing* is needed by all systems for in-core and structural systems, as well as for balance-of-plant, fuel recycle, and energy conversion equipment. This underscores the need to revitalize U.S. test capabilities for nuclear-rated materials.
- *Spent fuel treatment* needs to be developed and demonstrated, and recycle facilities developed and constructed for one of the following systems GFR, LFR, and SFR, which will be down selected in 2010.

The above R&D provides the major building blocks necessary to support the NGNP and the preferred fast reactor concept over the next ten years. Specific R&D milestones and activities are developed in the Program Plan.



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## **1 PURPOSE OF THE GENERATION IV TEN-YEAR PROGRAM PLAN**

The Generation IV Nuclear Energy Systems Program Plan identifies program objectives and priorities to provide programmatic direction within the U.S. Department of Energy (DOE) complex and among the program participants, including national laboratories, industry, universities, and international participants. Furthermore, for the upcoming ten years, the plan gives an overview of the integrated program and how the goals identified in the *Generation IV Technology Roadmap*<sup>7</sup> will guide the research and development (R&D). The plan reflects the priorities of the *U.S. Generation IV Implementation Strategy*<sup>8</sup> reported to the Congress in September, 2003. The plan also describes the relationship and interactions between the Generation IV Program and the Advanced Fuel Cycle Initiative (AFCI). Detailed plans for the systems and crosscutting R&D are given in the nine technical appendices to this document.

## **2 GENERATION IV PROGRAM DESCRIPTION**

The Generation IV program is managed by the DOE Office of Nuclear Energy, Science, and Technology with the objective of advancing nuclear energy to meet future energy needs. Through a common interest in nuclear energy, the U.S. DOE and organizations in ten other countries formed a framework for international cooperation known as the Generation IV International Forum.

### **2.1 Introduction**

Generation IV connotes the next generation of nuclear energy systems. From the 1940s to the present, there have been three previous generations. Generation I consisted of the early prototype reactors of the 1950s and 1960s including Shippingport, Dresden, and Magnox. The Generation II systems, following after Generation I, began in the 1970s and comprise the large commercial power plants such as the pressurized water reactors and boiling water reactors in the United States. Many Generation II plants are still operating today. The Generation III nuclear systems were developed in the 1990s and include a number of evolutionary designs that offer significant advances in safety and economics. A number of Generation III systems have been built, primarily in East Asia.

The first three generations of nuclear energy have been successful in the following ways:

- (1) Nuclear energy supplies a significant share of electricity for today's needs—over 20% of U.S. and 16% of world demand.
- (2) Nuclear energy plays a large role in the U.S. economy. In 2002, the 103 operating U.S. nuclear power plants generated 790 billion kilowatt-hours of electricity, valued at \$50 billion.
- (3) Through the use of nuclear energy, the United States has avoided over three billion tons of air emissions since 1970.

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<sup>7</sup>“A Technology Roadmap for Generation IV Nuclear Energy Systems,” *Generation IV International Forum*, GIF-002-00, December 2002, available at <http://www.inel.gov/initiatives/generation.shtml>, accessed January 2004.

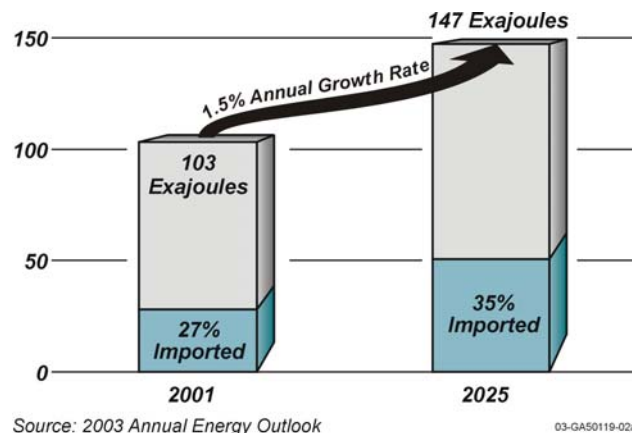
<sup>8</sup>“The U.S. Generation IV Implementation Strategy,” *U.S. Department of Energy*, September, 2003, available at <http://nuclear.gov/geniv/gen-ivstrategy.html>, accessed January 2004.

- (4) U.S. nuclear plants are highly reliable and in 2001 produced electricity for 1.68 cents per kilowatt-hour on average. This low cost is second only to hydroelectric power among baseload generation options.
- (5) In return for access to peaceful nuclear technology, over 180 countries have signed the Non-Proliferation Treaty to help ensure that peaceful nuclear activities will not be diverted to making nuclear weapons.

Although nearly all U.S. light water reactors are expected to file for 20-year license extensions, it is clear that new nuclear energy systems need to address issues of safety, economics, waste, and proliferation resistance with a robust R&D program. Advances in all of these areas can contribute to increasing the sustainability of nuclear energy.

**U.S. Energy Demand Outlook:** The outlook for energy demand in the United States underscores the need to increase the share of nuclear energy production. The *Annual Energy Outlook*,<sup>9</sup> produced by the Energy Information Administration of DOE, projects an annual growth rate of 1.5% in total energy consumption to the year 2025 (see Figure 2.1). At the same time, domestic energy production will grow only 0.9% per year, creating a widening gap to be filled by energy imports. Further, most of the projected domestic energy production increase is to be provided by coal and natural gas. Thus, the outlook implies an increasing burden from carbon emissions with the potential for long-term consequences from global climate change, as well as an increasing dependence on foreign energy sources. These create a strong motivation for seeking to increase the share of nuclear-generated electricity above its current 20% level.

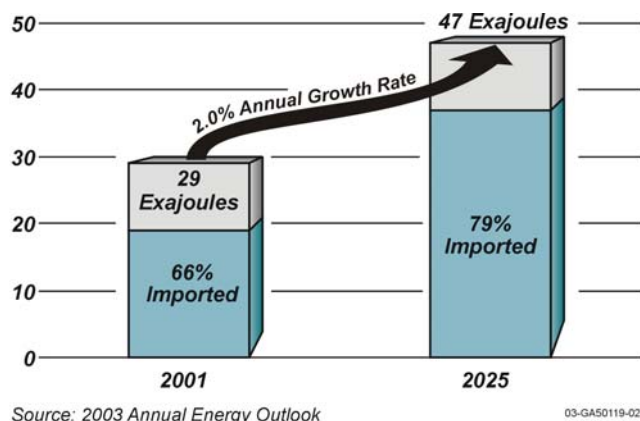
The outlook for energy demand within the major sectors of energy use other than electricity also points out an emerging role for nuclear energy in hydrogen production. *Energy Outlook* projects an annual growth of 2.0% per year for the transportation sector (see Figure 2.2), while the electricity and heating sectors will grow at 1.4% and 1.2%, respectively. Transportation is almost exclusively dependent on petroleum. This dependence has caused fluctuations in fuel prices of 30% and several “energy shocks” since the 1970s. This volatility creates a significant need for seeking to diversify with new fuels, such as hydrogen for use in emissions-free fuel cells that power electric vehicles. Large-scale production of hydrogen by nuclear energy would be free of greenhouse gas emissions. To achieve these benefits, new nuclear energy systems that are specialized for hydrogen production at competitive prices need to be developed.



**Figure 2.1** Projected U.S. Energy Demand

<sup>9</sup> “The Annual Energy Outlook 2004,” *Energy Information Administration*, available at <http://www.eia.doe.gov/oiaf/aeo/>, accessed February 2004. Note that the *Generation IV Implementation Strategy* was based on the *Annual Energy Outlook 2003*, which is substantially the same as the current update.

Thus, in addition to short-term nuclear deployment, two long-term technology development objectives for nuclear energy in the U.S. are derived from the needs identified above: (1) Develop advanced nuclear energy systems that can address the barriers to growth and significantly increase the share of nuclear electric generation while increasing their sustainability in the long term, and (2) Develop systems for nuclear-generated hydrogen that can diversify the energy supply for the transportation sector and reduce the dependence on petroleum.



**Figure 2.2** Projected U.S. Transportation Energy Demand

Beginning in January 2000, ten countries and Euratom have joined together to form the Generation IV International Forum (GIF<sup>10</sup>) to develop future-generation nuclear energy systems that can be licensed, constructed, and operated to provide competitively priced and reliable energy products while satisfactorily addressing nuclear safety, waste, proliferation, and public perception concerns. The overarching objective for Generation IV systems is to have them available for international deployment before the year 2030.

**The Generation IV Roadmap:** From its beginning, the GIF discussed the R&D necessary to support next-generation nuclear energy systems. From those discussions a technology roadmap to guide the Generation IV systems began and was completed in two years with the participation of over 100 experts from the GIF countries. The effort ended in December 2002 with the issue of the final Generation IV Technology Roadmap.<sup>11</sup> Especially noteworthy was the recognition gained by the U.S. by leading the formation of the GIF and the development of the technology roadmap. This has helped to strengthen U.S. leadership in the peaceful uses of nuclear energy and to underscore the importance of collaborative R&D on future nuclear energy systems.

The roadmap evaluated over 100 future systems proposed by researchers around the world. The scope of the R&D described in the roadmap covers the six most promising Generation IV systems. It is important to note that each GIF country will focus on those systems and the subset of R&D activities that are of greatest interest to them. Thus, the roadmap provides a foundation for formulating national and international program plans on which the GIF countries will collaborate to advance Generation IV systems.

<sup>10</sup> Argentina, Brazil, Canada, Euratom, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States currently constitute the GIF. New members can be added by a process outlined in the GIF charter.

<sup>11</sup> "A Technology Roadmap for Generation IV Nuclear Energy Systems," *Generation IV International Forum*, GIF-002-00, December 2002, available at <http://www.inel.gov/initiatives/generation.shtml>, accessed February 2003.

The roadmap identified six most promising systems. Two employ a thermal neutron spectrum with coolants and temperatures that enable hydrogen or electricity production with high efficiency (the Supercritical Water-Cooled Reactor—SCWR and the Very High Temperature Reactor—VHTR). Three employ a fast neutron spectrum to enable more effective management of actinides through recycling of most components in the discharged fuel (the Gas-cooled Fast Reactor—GFR, the Lead-cooled Fast Reactor—LFR, and the Sodium-cooled Fast Reactor—SFR). The Molten Salt Reactor (MSR) employs a circulating liquid fuel mixture that offers considerable flexibility for recycling actinides, and may provide an alternative to accelerator-driven systems.

**Generation IV Goals:** The high-level objective of the Generation IV Program is to advance the systems in accordance with DOE priorities for their deployment in the U.S. The advancement of each system is measured in terms of its ability to meet the Generation IV goals: Eight goals for Generation IV [see box] are defined in the four broad areas of sustainability, economics, safety and reliability, and proliferation resistance and physical protection. An abbreviated description of each broad goal area, excerpted from the Roadmap, is given below.

*Sustainability is the ability to meet the needs of present generations while enhancing and not jeopardizing the ability of future generations to meet society's needs indefinitely into the future.* There is a growing desire in society for the production of energy in accordance with sustainability principles. Sustainability requires the conservation of resources, protection of the environment, preservation of the ability of future generations to meet their own needs, and the avoidance of placing unjustified burdens upon them.

*Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems.* Future nuclear energy systems should accommodate a range of plant ownership options and anticipate a wider array of potential roles and options for deploying nuclear power plants, including load following and smaller units. While it is anticipated that Generation IV nuclear energy systems will primarily produce electricity, they will also help meet anticipated future needs for a broader range of energy products beyond electricity. For example, hydrogen, process heat, district heating, and potable water will likely be needed to keep up with increasing worldwide demands and long-term changes in energy use. Generation IV systems have goals to ensure that they are economically attractive while meeting changing energy needs.

#### **Goals for Generation IV Nuclear Energy Systems**

**Sustainability-1** Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.

**Sustainability-2** Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.

**Economics-1** Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

**Economics-2** Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

**Safety and Reliability-1** Generation IV nuclear energy systems operations will excel in safety and reliability.

**Safety and Reliability-2** Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

**Safety and Reliability-3** Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

**Proliferation Resistance and Physical Protection-1** Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

*Safety and reliability are essential priorities in the development and operation of nuclear energy systems.* Nuclear energy systems must be designed so that during normal operation or anticipated transients safety margins are adequate, accidents are prevented, and off-normal situations do not deteriorate into severe accidents. At the same time, competitiveness requires a very high level of reliability and performance for Generation IV systems; as such their goals have been set to achieve high levels of safety and reliability through further improvements. The three safety and reliability goals seek simplified designs that are safe and further reduce the potential for severe accidents and minimize their consequences. The achievement of these ambitious goals cannot rely only upon technical improvements, but will also require systematic consideration of human performance as a major contributor to the plant availability, reliability, inspectability, and maintainability.

*Proliferation resistance and physical protection are also essential priorities in the expanding role of nuclear energy systems.* The safeguards provided by the Nuclear Nonproliferation Treaty have been highly successful in preventing the use of civilian nuclear energy systems for nuclear weapons proliferation. This goal applies to all inventories of fissile materials in the system involved in mining, enrichment, conversion, fabrication, power production, recycling, and waste disposal. In addition, existing nuclear plants are highly secure and designed to withstand external events such as earthquakes, floods, tornadoes, plane crashes, and fires. This goal points out the need to increase public confidence in the security of nuclear energy facilities against terrorist attacks. Advanced systems need to be designed from the start with improved physical protection against acts of terrorism, to a level commensurate with the protection of other critical systems and infrastructure.

The approach for achieving the Generation IV Nuclear Systems Program goals is to undertake the R&D tasks outlined in the Roadmap for the various systems and crosscutting technologies. The R&D tasks will be updated based on the key research findings that arise during the Generation IV effort over the subsequent years. Again, the tasks reflect current understanding of potential collaborative efforts by other countries, and will be updated as multilateral agreements are finalized.

## **2.2 Priorities for the Generation IV Program**

For each of the six systems above, the Roadmap develops the R&D needs in considerable detail and highlights the major R&D issues, benefits, and risks. The specific R&D issues and risks, identified in the roadmap and reviewed by the NERAC Subcommittee on Generation IV Technology R&D Planning, had a strong bearing on the prioritization of the systems versus the U.S. needs and technology objectives discussed above. From these studies and interactions, the following two principal priorities emerged:

***Priority 1:*** Develop a VHTR to achieve economically competitive hydrogen production in the mid-term.

The highest priority on developing a capability for nuclear-generated hydrogen with the VHTR reflects the excellent potential for this system to provide a major competitive advance toward the long-standing need to diversify the energy supply of the U.S. transportation sector. Successful development of an economically competitive nuclear-generated hydrogen supply will be aimed to deploy a VHTR that is dedicated to hydrogen production research and demonstration. To begin the effort, a nuclear hydrogen roadmap was completed in fiscal year (FY) 2003. This

effort is projected to be able to complete its key R&D by about 2012 and is partially enabled by many prior developments in high-temperature gas-cooled reactors internationally. As a result, completion and startup of a demonstration VHTR may be possible by 2016. This would be the earliest Generation IV system in the United States.

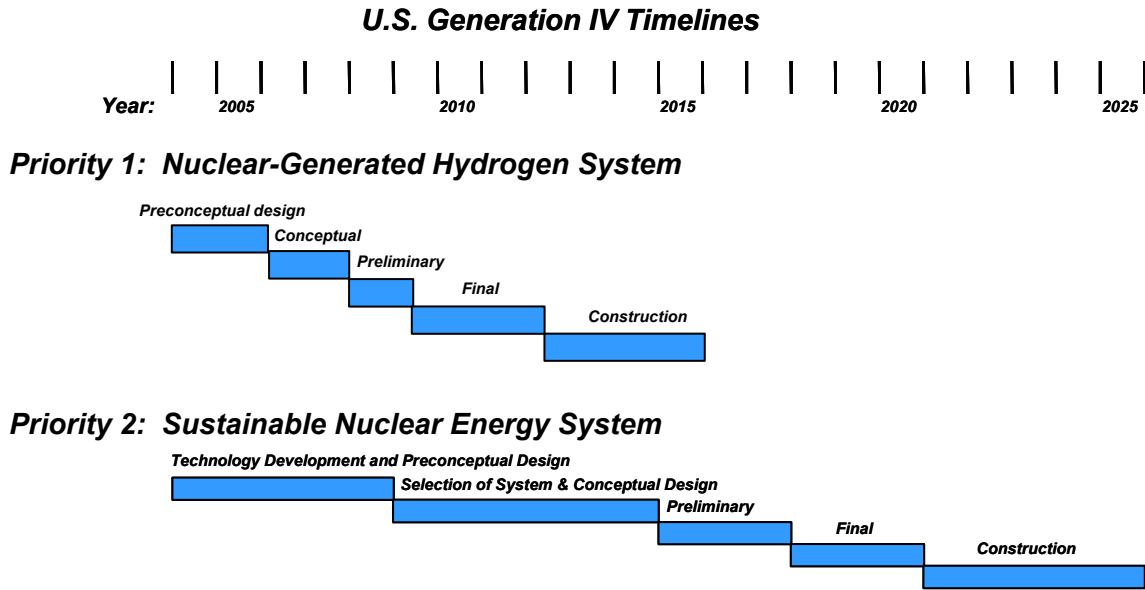
The development of a VHTR would have a number of associated benefits including the establishment of a basis for development of a fast-spectrum gas reactor discussed in the next priority.

**Priority 2:** Develop a fast reactor to achieve significant advances in sustainability for the long term.

The high priority on fast reactors reflects their good potential to make significant gains in reducing the volume and radiotoxicity and increasing the manageability of spent nuclear fuel wastes. The advances may be able to avoid a second geological repository. Fast reactors also hold the potential for extending the useful energy yield of the world's finite uranium supply many-fold in the very long term. The chief issues in the development of a next-generation fast-spectrum reactor for use in the United States are its economic competitiveness and management of the overall risks to workers and the public from the deployment of a closed fuel cycle.

Three of the most promising Generation IV systems are fast-spectrum (the GFR, LFR, SFR) for enhanced sustainability, and one (the MSR) employs a reactor specialized for actinide destruction. Among these, the LFR and GFR will be given the most emphasis in order to resolve technical issues and uncertainties, since these reactors offer strong potential benefits that have not been fully demonstrated. The SFR is already at a fairly advanced state of development, with many of its technologies having been demonstrated internationally. All of these systems should be brought to a state where a downselection on economics, safety and reliability, sustainability, and proliferation resistance and physical protection can be undertaken. Finally, the MSR should be studied with a lower priority, given the system's uncertainties and development needs. The ultimate selection of the most promising system will likely be driven by fuel cycle decisions that will follow from the Advanced Fuel Cycle Initiative as well as the development of an effective fast transmutation system

The most direct influence of these priorities for the U.S. Generation IV Program is in the allocation of R&D resources between the systems in the program plan. An additional area of R&D is the crosscutting research needed by these systems. Arising from the common need for advances against challenging requirements on fuels and materials, fuel cycle technology, and system design to achieve highly safe and reliable systems, these crosscut areas are given the



**Figure 2.3** Timelines for U.S. Priority 1 & 2 Systems

most emphasis. Energy conversion technology is another important need also highlighted in the program plan. Specific, yet limited, activities are found in other crosscutting areas that are not as directly involved in the feasibility of the priority systems.

Timeframes for the Generation IV Systems: Proposed timelines (see Figure 2.3) for the two priorities are shown above. For the development of a VHTR in Priority 1, a 12-year timeline is to be implemented. This balances the benefit of demonstrating a large-scale economically competitive nuclear hydrogen system with the technical issues and risks establishing an aggressive schedule for its development.

For the development of a fast-spectrum reactor in Priority 2, a 20–25-year timeline is to be implemented. This fits with the expected future need for radiotoxicity reduction and closure of the U.S. nuclear fuel cycle, and allows the progression of several most promising candidates to a downselection in about a decade, followed by a demonstration of all elements of a closed fuel cycle within about a decade thereafter.

Presently, plans have been formulated for implementation of R&D projects in the U.S. to support these systems and their associated crosscutting R&D needs. These plans are given in the subsequent chapters. Plans by other GIF members to advance these systems are reflected in this plan from available information. Future updates to this plan will be made as the plans of the other countries are completed and collaborations are formalized in implementing arrangements.

### **2.3 R&D Programs for Individual Generation IV Systems**

The Generation IV Roadmap facilitates the assembly of larger R&D programs or smaller projects on which the GIF countries choose to collaborate. Entire programs consist of all or most of the R&D needed to advance a system. Individual country projects consist of R&D on specific technologies (either system-specific or crosscutting) or on subsystems that are needed for a Generation IV system. In either case, the program or project is focused on key technology issues

and milestones. This section highlights the major milestones and development needs that have been identified for the collective R&D activities.

Table 2.1 gives the objectives and endpoint products of the R&D, or *endpoints*. The R&D activities in the Generation IV plan have been defined to support the achievement of these endpoints.

The *viability* phase R&D activities examine the feasibility of key technologies. Examples of these include adequate corrosion resistance in materials in contact with lead alloys or supercritical water, fission product retention at high temperature for particle fuel in the very-high-temperature gas-cooled reactor, and acceptably high recovery fractions for transuranic actinides for systems employing actinide recycle.

**Table 2.1** Generation IV Objectives & Endpoints

<b>Viability Phase Objective:</b>  Basic concepts, technologies and processes are proven out under relevant conditions, with all potential technical <i>show-stoppers</i> identified and resolved.	<b>Performance Phase Objective:</b>  Engineering-scale processes, phenomena, and materials capabilities are verified and optimized under prototypical conditions
<b>Viability Phase Endpoints:</b>  1. Preconceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams  2. Basic fuel cycle and energy conversion (if applicable) process flowsheets established through testing at appropriate scale  3. Cost analysis based on preconceptual design  4. Simplified PRA for the system  5. Definition of analytical tools  6. Preconceptual design and analysis of safety features  7. Simplified preliminary environmental impact statement for the system  8. Preliminary safeguards and physical protection strategy  9. Consultation(s) with regulatory agency on safety approach and framework issues	<b>Performance Phase Endpoints:</b>  1. Conceptual design of the entire system, sufficient for procurement specifications for construction of a prototype or demonstration plant, and with validated acceptability of disposal of all waste streams  2. Processes validated at scale sufficient for demonstration plant  3. Detailed cost evaluation for the system  4. PRA for the system  5. Validation of analytical tools  6. Demonstration of safety features through testing, analysis, or relevant experience  7. Environmental impact statement for the system  8. Safeguards and physical protection strategy for system, including cost estimate for extrinsic features  9. Pre-application meeting(s) with regulatory agency

The *performance* phase R&D activities undertake the development of performance data and optimization of the system. Although general milestones were shown in the Roadmap, specific

milestones and dates will be defined based on the viability phase experience. As in the viability phase, periodic evaluations of the system progress relative to its goals will determine if the system development is to continue. The viability and performance phases will likely overlap because some of the performance R&D activities may have long lead times that require their initiation as early as possible.

Assuming the successful completion of viability and performance R&D, a *demonstration* phase of at least six years is anticipated for any system, requiring funding of several billion U.S. dollars. This phase involves the licensing, construction, and operation of a prototype or demonstration system in partnership with industry and perhaps other countries. The detailed design and licensing of the system will be performed during this phase.

## **2.4 Performance Indicators and Exit Criteria**

Successful completion of the viability and performance phases will only be achieved if all performance indicators for these phases are satisfied. The viability and performance phase indicators are essentially go-no go measures of whether the system under consideration will be able to meet the Generation IV goals. For example, since a key requirement for successful completion of the NGNP viability phase is the development and demonstration of materials that can withstand an average bulk gas temperature of 1000 °C on a long-term basis, successful development of such a material is the satisfactory completion of one of the NGNP viability phase performance indicators. The results describing whether or not a key viability phase performance indicator is achieved is termed a Generation IV research and development (R&D) output. Successful completion of the NGNP viability phase requires satisfactory completion of all the viability phase performance indicators, i.e., satisfactory outputs. Successful completion of the NGNP viability phase is defined as an outcome of the Generation IV research & development effort (see Section 2.4.1). Failure to meet any of the NGNP viability phase performance indicators likely will mean the NGNP system would not be a viable Generation IV system.

The long-term goal of the Generation IV program is to develop next-generation nuclear energy systems for deployment in the 2015-2030 time frame. Performance indicators are used to assess the progress of individual reactor development programs towards this long-term goal within the Department. These indicators are separated into two categories—outputs and outcomes—as described below.

### **2.4.1 Performance Indicator Outputs**

R&D outputs are typically specified on an annual basis. They are focused on individual technical issues or concept-specific milestones. Examples of outputs supporting the successful completion of the viability phase (the first outcome given in Section 2.4.2) include the following concept or crosscut items.

- NGNP – development of a qualified particle fuel
- NGNP – development of structural materials that can withstand sustained operational temperatures of 1000 °C
- SCWR – specification of a reactor safety approach
- GFR – selection of fuel and core structural materials

- LFR – Determination of a nitride fuel fabrication method
- Energy Products – successful demonstration of a supercritical carbon dioxide cycle for electricity production

Examples of outputs supporting the successful completion of the performance phase (the second outcome given in Section 2.4.2) include the following items.

- Completion of a reactor system design that is sufficient to support commercialization and regulatory approval
- Resolution of fabrication and manufacturing issues for major system components and fuel
- Demonstration by analysis that the major economic, safety, sustainability, and security goals are met

The priorities of the Department of Energy and the budget available to the Generation IV program will drive which outputs or milestones are actively scheduled for R&D and completion.

#### **2.4.2 Performance Indicator Outcomes**

The term “outcome” is defined as an ultimate, significant result of the R&D work that is being performed under the Generation IV program. The first outcome is the resolution of all viability issues. A second outcome is the development of one or more Generation IV reactor systems to the point that allows construction of a prototype or demonstration plant. In the long term, the final outcome is the commercialization of one or more Generation IV reactor concepts

#### **2.4.3 Exit Criteria**

If any particular concept proves not to be viable during the viability phase, then the concept will be dropped from further consideration. If certain aspects of a reactor concept prove not to be viable without necessarily eliminating the concept altogether, alternatives will be examined and researched, within the limits of schedule and budget, to make the overall concept viable.

Upon reaching the performance phase, a specific concept has been proven to be viable, but construction of a prototype or a demonstration plant is still not assured. The R&D work must be directed to show that the concept can deliver on its promised potential both technically and economically. The decision not to pursue construction of a prototype or demonstration plant can still be made based upon unfavorable performance phase results.

### **2.5 International Program Implementation**

The R&D on the Generation IV systems will be implemented in an international framework, with participation by the GIF members<sup>12</sup>. Participation by specialists or facilities in other

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<sup>12</sup> Argentina, Brazil, Canada, Euratom, France, Japan, the Republic of Korea, the Republic of South Africa, Switzerland, the United Kingdom, and the United States.

countries is desired, and will be funded by individual member countries. The GIF is discussing the organization and conduct of its programs, and these agreements may be in place as early as FY 2004.

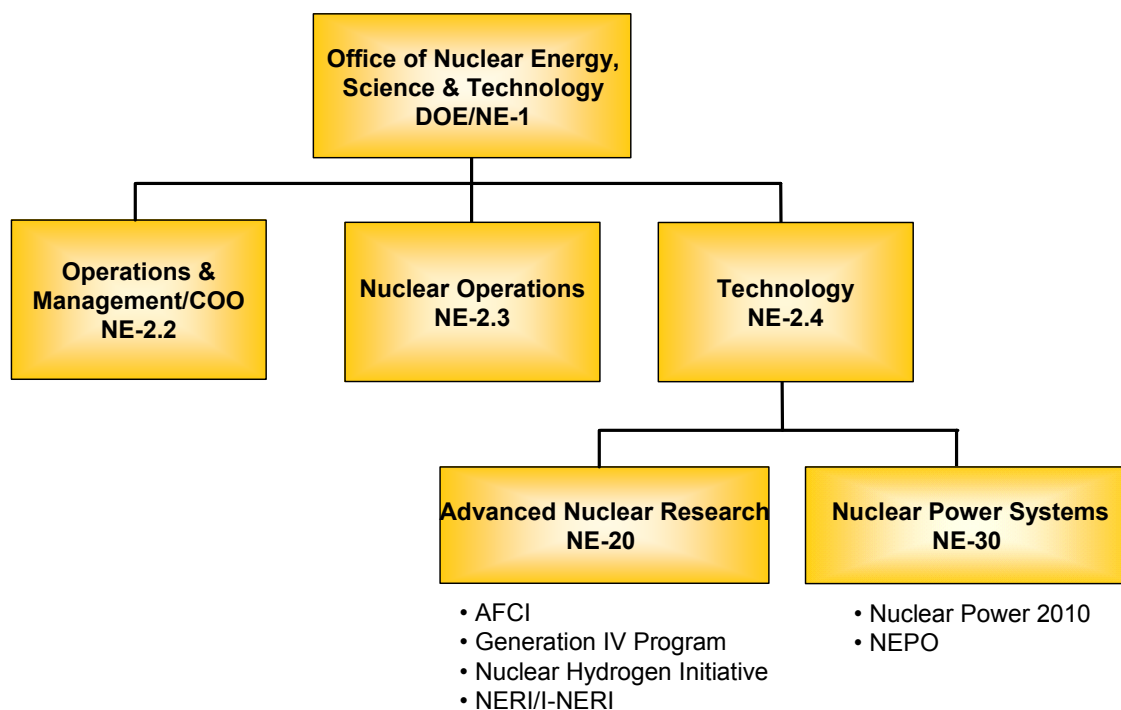


The GIF expects to define cooperative System Agreements under which multiple countries participate in research projects. The agreements will establish the R&D objectives, obligations, intellectual property rights, dispute resolution and other necessary items. For any Generation IV system, multiple projects will be defined that are governed by Project Arrangements. For example, development of fuel for a given system may constitute a project. The systems and projects described in this plan will be considered for inclusion in such agreements, and have been specified to avoid overlaps with known or projected activities in the other countries.

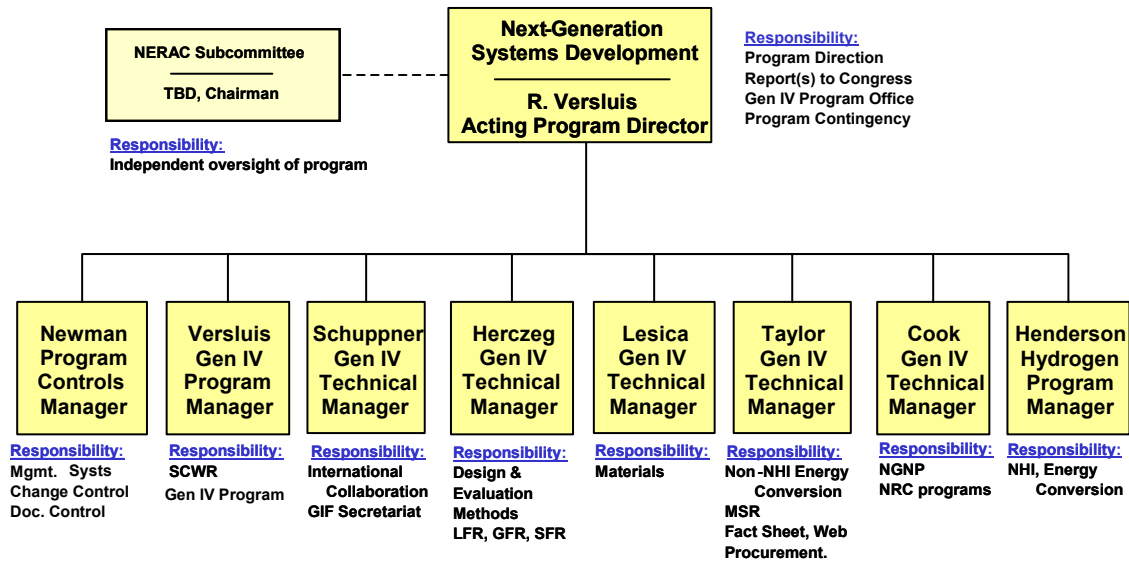
### 3 PROGRAM ORGANIZATION AND RESPONSIBILITIES

#### 3.1 Organizational Structure

The Office of Nuclear Energy, Science and Technology (NE) (see Figure 3.1) is responsible for leading the Federal government's investment in nuclear science and technology. The Nuclear Energy Program represents the core of the U.S. Government's expertise in nuclear engineering and technology. NE activities help to maintain the nation's access to diverse and environmentally responsible sources of energy and advance the country's economic and technological competitiveness. The Generation IV Nuclear Energy Systems Program is closely linked to another NE Program: the Advanced Fuel Cycle Initiative (AFCI). The AFCI mission is to strengthen the future of nuclear power by addressing the spent nuclear fuel issue. The primary goals of the AFCI are to: (a) develop and implement advanced fuel cycle technologies to significantly reduce the long-term cost of geological disposal of commercial spent nuclear fuel, and (b) develop methods to reclaim the energy value from highly toxic spent fuel while providing for their destruction. By integrating the AFCI and Generation IV Program through a common systems analysis function, NE has established a structure that will facilitate the coordination of both programs to support a unified R&D effort. Within this structure, the Generation IV Nuclear Energy Systems Program has been organized to maximize and leverage technical functional expertise while enhancing communication between program participants through systems analysis and technical integration. Figure 3.2 shows the DOE/NE program office organization.



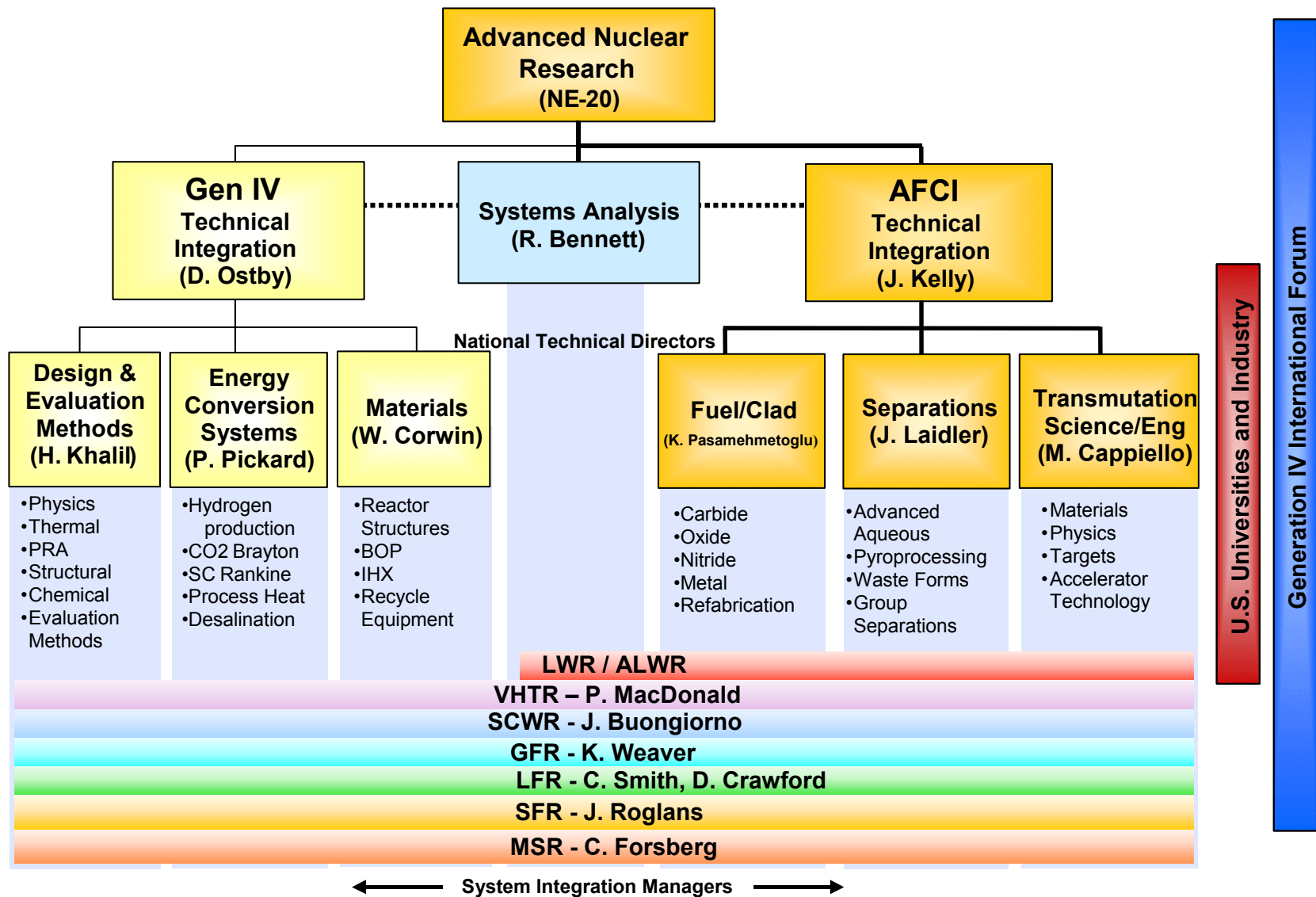
**Figure 3.1.** Nuclear Energy Organizational Structure



**Figure 3.2.** Generation IV Program Organizational Structure

### 3.2 Roles and Responsibilities

The AFCI and Generation IV programs have an integrated management structure, sharing a common systems analysis function. Roles and responsibilities for key Generation IV Program functions are shared among the headquarters organizations of NE, Technical Integration, Project Controls, Systems Analysis, the System Integration Managers for the specific systems, and the National Technical Directors for each of the three functional disciplines of the Generation IV Program – System Design & Evaluation, Materials, and Energy Conversion Systems. System integration teams are established to address crosscutting issues throughout the functional program elements of the AFCI and Generation IV Program. A schematic diagram of this functional structure and organization is shown in Figure 3.3. Specific roles and responsibilities for each of these functional groupings are described below.



**Figure 3.3** APCI and Generation IV Program Organizational Structure

### **3.2.1 DOE Office of Nuclear Energy, Science, and Technology (DOE NE)**

Essential programmatic functions include, but are not limited to, the following:

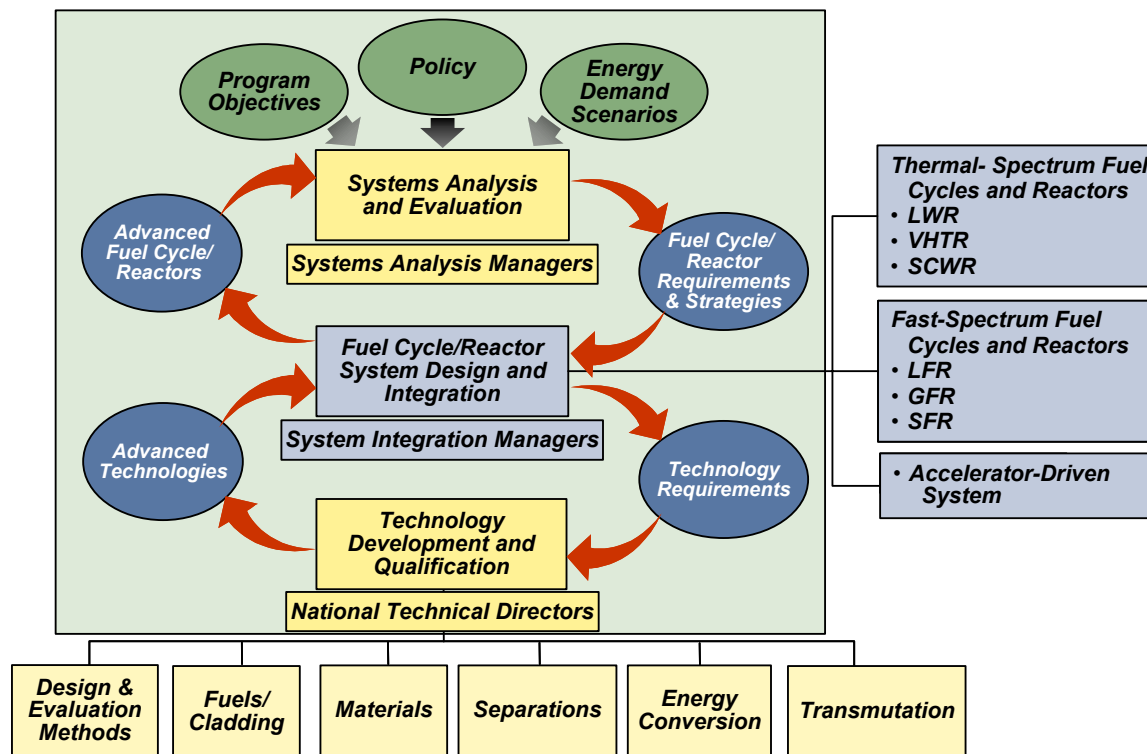
- Manage the development of a programmatic strategic plan.
- Establish program policy and issue programmatic guidance.
- Develop program requirements, standards, and procedures.
- Establish performance measures and perform annual performance reviews.
- Manage programmatic planning and processes.
- Coordinate, review, comment on, and approve final Generation IV Program Plan.
- Review, comment on, and give final approval to all tasks.
- Evaluate and assess program progress.
- Provide program interface to external organizations including Office of Civilian Radioactive Waste Management (DOE-RW), National Policy Agencies, Nuclear Energy Research Advisory Committee (NERAC), the proposed Generation IV Subcommittee of NERAC, and foreign government and non-governmental entities.
- Manage and approve international agreements and foreign travel.

### **3.2.2 Integrated Generation IV and AFCI Function Teams**

The functional relationships specific to the important technology development and qualification R&D efforts in AFCI and the Generation IV Program are centered in six areas: design and evaluation methods, fuels/cladding, materials, separations, energy conversion, and transmutation and are headed by the National Technical Directors (NTDs) as shown in Figure 3.4. The NTDs use common technology requirements to provide advanced technologies for the specific Generation IV systems. The System Integration Managers (SIMs) also work with the NTDs to define unique AFCI/Generation IV system R&D requirements and develop the R&D projects to meet them. The NTD-based common R&D efforts combined with the R&D efforts identified by the SIMs for the Generation IV systems comprise the total Generation IV Program and AFCI R&D portfolio. The SIMs and NTDs interact as illustrated in Figure 3.4.

The NTD-based and SIM-based R&D are aimed at satisfying the viability phase and performance phase outcomes that meet the AFCI and Generation IV goals. The process is tracked, and modified as needed, by systems analysis in response to policy decisions, energy

demand scenarios, and changes in requirements and strategy that arise as the AFCI and Generation IV Program evolves.



**Figure 3.4.** Integrated Generation IV and AFCI Functional Teams

### 3.2.3 Systems Analysis

The systems analysis function develops and applies tools to formulate, assess, and steer program activities to meet programmatic goals and objectives, including:

- Integrate R&D by formulating recommendations to focus program development direction.
- Integrate program level systems analysis for both AFCI and Generation IV.
- Deploy system tools to develop recommended priorities for technology development.
- Develop sustainability metrics encompassing economics, environmental, and societal aspects, capable of:
  - Evaluating nuclear systems and fuel cycles, and
  - Comparing nuclear energy with other means of producing primary energy.

The systems analysis function is led by the National Technical Director for Systems Analysis, with oversight of both Generation IV and AFCI.

### **3.2.4 System Integration Teams**

System integration teams for each Generation IV system address the technical issues and develop R&D plans that identify the milestones and deliverables that support their innovative systems and new facilities with key R&D activities. System integration teams are identified for each Generation IV system and each is headed by a System Integration Manager (SIM). SIMs are identified that bring substantial technical credentials and leadership. The product teams:

- Define major APCI facility and Generation IV system requirements.
- Develop product-specific R&D technology roadmaps using interdisciplinary teams
- Analyze and advance the progress of the system or facility each year.
- Support the major program decisions on the selection of their system or facility.

### **3.2.5 National Technical Directors**

The National Technical Directors (NTDs) manage crosscut R&D activities including:

- Develop and maintain targeted crosscut area research, including the implementation of the Generation IV Program Ten-Year Plan.
- Direct development of proposed tasks and manage scope, cost, and schedule of the crosscut area; Support product team efforts to ensure integration of product requirements into the research and development activities.

### **3.2.6 Technical Integration**

The technical integration function integrates program technical activities including:

- Coordinate and implement technical program guidance with the National Technical Directors.
- Develop and update as necessary the Generation IV Program Ten-Year Plan.
- Develop and maintain external communication products for the Generation IV Program, such as congressional reports, fact sheets, displays, and web pages. Coordinate Generation IV Program conference participation and publications.
- Coordinate, facilitate, and manage quarterly and semi-annual meetings and all other major Generation IV Program meetings.
- Develop monthly and quarterly reports.
- Coordinate with Project Controls and track tasks to ensure that scope, cost, and schedule are met, including milestones. Alert DOE NE to all potential problems or issues.

### **3.2.7 Project Controls**

The Generation IV R&D program is managed according to the principles of DOE Order 413.3, Program and Project Management for the Acquisition of Capital Assets. This Order will be fully adhered to for all capital projects developed under the program.

On an annual basis, DOE/NE will provide draft budget guidance to the national laboratory participants based upon technical activities outlined in this Plan, which will be updated as necessary. Upon receiving the draft budget guidance from DOE/NE, each participant develops draft work packages that include cost, schedule, and scope by individual Work Breakdown System (WBS) elements consistent with this Plan. The National Technical Directors and the Technical Integrator review the draft work packages for completeness and overall program integration. The draft work packages are then reviewed and revised (if necessary) by DOE/NE, who then distributes final fiscal year budget guidance for each participant. Program participants revise and finalize their work packages based upon the budget guidance. The National Technical Directors and the Technical Integrator again review the final work packages for completeness and integration, and DOE/NE reviews them for final approval. Once DOE/NE approves the work packages, they establish the cost, schedule and technical baselines for each participant and establish the overall integrated program baseline.

A program controls system has been established to monitor the performance of work packages once they are approved. The status of each work package is evaluated monthly by the relevant NTD, the HQ lead, the Technical Integrator, and the Program Controls group to assess performance. For work packages where the variance from the baseline exceeds a threshold, a more in-depth evaluation is initiated and a corrective action plan initiated as necessary.

### **3.3 Generation IV Program Management Processes**

The Generation IV Program is managed in accordance with DOE Order 413.3, Program and Project Management for the Acquisition of Capital Assets. DOE Headquarters will provide a high level Program Plan which supports the "Government Performance Results Act" (GPRA), and provides the overall view and direction of the Generation IV program. This program plan is a vehicle for planning and executing the program at the laboratories. Each year DOE-NE will provide draft budget guidance to the national laboratories and other participants based upon their technical capabilities and facilities as well as the input of the Technical Integrator and the National Technical Directors.

Upon receiving the draft budget guidance, each participant develops draft work packages that include cost, schedule, and scope by individual work breakdown system (WBS) elements. The Technical Integrator and the National Technical Directors review the draft work packages for completeness and overall program integration. The draft work packages are then reviewed by DOE-NE who develops and distributes final fiscal year budget guidance for each participant pending approval. Program participants revise and finalize their work packages based upon the budget guidance. The Technical Integrator and the National Technical Directors again review the final work packages for completeness and integration, and DOE-NE reviews for final approval. The approved DOE-NE work packages establish the cost, schedule, and technical baselines for each participant and establish the overall integrated program baseline.

The Technical Integrator and the National Technical Directors monitor program performance against the established baseline. Changes to the baseline must be approved through the Generation IV Change Control Process. These baselines also support the development of performance metrics for each participant that are used in the program reviews conducted by the Generation IV Program.

### **3.4 Key Program Assumptions, Uncertainties, and Risks**

A number of critical assumptions form the planning basis for the Generation IV Program. Associated with each assumption, there is a degree of uncertainty, which represents some risks to the program. These risks include both technical risks and programmatic risks.

#### **3.4.1 Assumptions and Uncertainties**

##### ***Planning Budget***

This plan assumes a FY 2004 budget of \$27.7 million, based on the Congressional appropriation enacted in December 2003. The FY 2005 budget request is \$30.5 million. The budgets for FY 2006 through FY 2014 are based on the required levels as presented in Section 5. It also assumes support for a robust AFCI Program, including sufficient funding to develop Generation IV fuels in the AFCI.

##### ***Major Facilities Schedule***

DOE will lead the effort to perform the R&D and engineering scale experiments and demonstrations to achieve sufficient technical readiness levels and provide industry with a high level of confidence in production-scale facility construction costs and schedules. DOE will participate with industry in facility design activities through preliminary design in order to achieve the desired confidence level. DOE expects industry to take the lead in construction and operation of the production facilities needed to implement Generation IV technologies, including fuel cycle facilities. Actual deployment dates will depend on industry's needs and economic factors, the same factors that will decide the future of nuclear energy in the U.S.

##### ***Gen IV Concept Selection***

It is assumed that at least one fast spectrum Gen IV reactor concept will be developed to provide the transmutation performance necessary to achieve the goals of AFCI Gen IV fuel cycle. An initial downselection may be possible around 2010, given sufficient funding.

##### ***Legacy Cleanup Costs***

The legacy cleanup costs associated with Generation IV Program testing activities have not been included in cost estimates provided in this plan.

#### **3.4.2 Technical Risks: Viability Phase to Performance Phase Transition**

Although the processes proposed for incorporating the results from a viability phase outcome to build the necessary hardware and facilities to enter the performance phase are well-understood, achieving the Generation IV Program goals has some technical risk associated with it. Technical risk is associated with moving from small-scale technology demonstrations to a production-scale plant. The role that intermediate, engineering-scale demonstrations can serve to mitigate this risk need to be examined.

### **3.4.3 Programmatic Risks**

#### ***Budget Allocation***

The Generation IV Program has aggressive schedules so that it can provide time-critical credible technical options. Substantial and stable long-term funding will be required to achieve this objective. It will be necessary for the program to continuously update its technical plan based on available funding levels.

#### ***Evolving National Policy***

A program, such as Generation IV, aimed at proving advanced reactor technology is capable of achieving the Generation IV Roadmap goals and ultimately at laying the groundwork for building advanced systems in the United States is subject to the regulations associated with licensing such plants and also national policy. The Generation IV Program management must monitor and/or recommend changes to these policies to ensure that proposed activities can be conducted within the requirements imposed.

#### ***Risk Mitigation***

A major role of the Technical Integrator, working with DOE and the national Technical Directors, is to identify, develop, and monitor mitigation strategies for both technical and programmatic risks associated with the Generation IV Program.

## **4 PROGRAM INTERFACES**

### **4.1 External**

External program interfaces exist with the Nuclear Energy Research Advisory Committee (NERAC), the U.S. Nuclear Regulatory Commission (NRC), and international and university partners as described below.

#### **4.1.1 Nuclear Energy Research Advisory Committee (NERAC)**

The NERAC was established on October 1, 1998, to provide independent advice to the DOE and NE on complex science and technical issues arising from the planning, management, and implementation of DOE's nuclear energy program. NERAC will periodically review NE program elements and, based on these reviews, provide advice and recommendations on long-range plans, priorities, and strategies to effectively address the scientific and engineering aspects of the R&D efforts. In addition, the committee will provide advice on national policy and scientific aspects of nuclear energy research issues as requested by the Secretary of Energy or the Director, NE. The committee includes representatives from universities, industry, and national laboratories. Particular attention was paid to obtaining a diverse membership with a balance of disciplines, interests, experiences, points of view, and geography.

The NERAC Subcommittee on Generation IV Nuclear Energy Systems Technology is in the process of being formed. It will review plans for the conduct of the Generation IV Nuclear Energy Systems Program and provide recommendations regarding program activities. This subcommittee will conduct regular reviews of program plans and activities.

#### **4.1.2 Nuclear Regulatory Commission (NRC)**

The NRC is an independent agency established by the Energy Reorganization Act of 1974 to regulate civilian use of nuclear materials. A five-member Commission heads NRC. NRC's primary mission is to protect the public health and safety, and the environment from the effects of radiation from nuclear reactors, materials, and waste facilities. NRC carries out its mission by commission direction-setting and policymaking, radiation protection, and regulation.

All proposed Generation IV concepts will require licensing by the NRC in their demonstration phase. Frequent interactions between the Generation IV Program and the NRC will be required to achieve timely licensing as required to achieve program goals.

#### **4.1.3 International Partners**

A major element of the Generation IV Program is a robust cooperative program with international partners. DOE will exchange information with its current international partners and will explore the potential for similar cooperation with other countries. This effort will greatly leverage the resources of the U.S. and other countries. The collaborations will be managed by multilateral cooperative agreements between GIF members, and by various bilateral agreements (such as I-NERI agreements) of the U.S. and individual countries.

The International-NERI (I-NERI) is a program developed by DOE/NE to foster international collaborative R&D on nuclear technology and global deployment. DOE/NE plans to sign bilateral I-NERI agreements with countries that are members of GIF. GIF members share a

common interest in developing advanced, next-generation reactor designs that offer advantages in terms of economics, safety, proliferation resistance, and waste minimization.

#### **4.1.4 University Partners**

DOE created the Nuclear Energy Research Initiative (NERI) in 1999 to address the principal technical and scientific concerns affecting the future use of nuclear energy in the U.S. Many NERI projects have combined the talents of U.S. universities, industry, and national laboratories to bring leading-edge solutions to Generation IV systems. NERI also helps preserve the nuclear science and engineering infrastructure within our nation's universities and the nuclear industry and to maintain a competitive position worldwide by advancing the state of nuclear energy technology. The DOE is in the process of folding NERI into the AFCI and Generation IV Program to better integrate the R&D effort. As a first step on March 4-5, 2004, DOE held the Advanced Reactor, Fuel Cycle, and Energy Products Workshop for Universities to provide U.S. universities the opportunity to become familiar with the research and development (R&D) requirements of the various programs of the Office of Nuclear Energy, Science and Technology. A solicitation is expected to be issued in early April 2004.

#### **4.2 Internal DOE Interfaces**

Internal interfaces exist with the Nuclear Power 2010 Program and AFCI. These important interfaces will share objectives and research results each year.

##### **4.2.1 Nuclear Power 2010 Program**

The DOE believes that it is critical to deploy new baseload nuclear generating capacity within the decade to support the National Energy Policy objectives of energy security and supply diversity. The Nuclear Power 2010 program is a joint government/industry cost-shared program to develop advanced reactor technologies and new regulatory processes, with the objective of the initiation of construction by 2005 and operation by 2010, of new nuclear power plants in the United States by the private sector. To meet this objective, it is essential to demonstrate the new, untested Federal regulatory and licensing processes for the siting, construction, and operation of new plant designs. In addition, independent expert analysis commissioned by the DOE and carried out by the NERAC has shown that R&D is needed on near-term advanced reactor concepts offering enhancements to safety and economics to enable these new technologies to come to market. The Generation IV Program must coordinate with the Nuclear Power 2010 program to ensure that the results of the R&D efforts complement the industry needs and the new regulatory processes.

##### **4.2.2 Advanced Fuel Cycle Initiative**

The AFCI Program is being executed in an integrated manner with the Generation IV Generation IV program. The AFCI program has the responsibility of developing both reactor fuels and supporting fuel cycle technologies for both the transitional and advanced fuel cycle for Generation IV reactors. Integration of these programs enhances cost effectiveness and maximizes the use of unique facilities.

Separately from Generation IV, AFCI is responsible for providing an effective transition strategy to address the legacy of the current open fuel cycle. The technologies needed to enable the transition from the open fuel cycle are primarily focused on technical issues associated with treating LWR (and ALWR) spent nuclear fuel, such as reducing the volume and heat generation (short-term) of material requiring geologic disposal. These issues are being addressed thought

the development and demonstration of advanced separations technologies and proliferation-resistant recycled fuels. The recycle fuels would then be used in existing and advanced light water reactors, and possibly gas-cooled reactors. This approach will provide technical options that could be used to optimize utilization of the nation's first repository and potentially delay or eliminate the technical need for an additional repository in this century. Research activities include developing proliferation-resistant separations processes and fuels to harvest the energy value of these materials to be recovered, while destroying significant quantities of plutonium in light-water reactors.

The advanced fuel cycle efforts of the AFCI are also addressing the fuel cycle options required for Generation IV reactors. This part of the program will develop fuel cycle technologies to destroy minor actinides in fast neutron spectrum systems, greatly reducing the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository. This will be accomplished through the development of a transmutation fuel cycle using Generation IV fast reactors and possibly accelerator-driven systems (ADS).



Technologies, and (v) High Performance Helium Turbine. The planned R&D in these areas is summarized below:

### ***System Design & Evaluation***

The system design, system safety analyses, and the integration of these activities are centered on the use of analytical tools that are sufficiently quality-assured and accepted by industry to perform the required tasks. The degree to which the analytical tools are validated & verified (V&V) prescribes the work that can be successfully performed, e.g., pre-conceptual design, final design, license submittal, etc. Rapid and successful completion of this work is essential not only for performing meaningful design calculations but also acceptable licensing calculations. The development of the NGNP requires extensive analyses for performing the following: reactor core and primary system design analyses, reactor safety system design analyses, plant design analyses, economic analyses, safety & licensing analyses, and others—including human factors, PRA, etc.

*Systems Design & Licensing Tools:* The tools required to perform pre-conceptual design, final design, and licensing calculations consist of thermal-hydraulics software, computational fluid dynamics (CFD) software, neutronics software, and mechanical assessment software<sup>14</sup>. Used together these tools will give a complete evaluation of the system behavior (peak material temperatures, core damage, peak fluid temperatures at turbine inlet, plant efficiency, etc). Although the tools needed to perform these functions largely exist they must be certified to show that they are capable of calculating the desired system behavior, viz, transients, steady-state conditions, etc.

*Economics, Human Factors, PRA, and Other Tools:* The tools used to perform economic evaluations, human factors, plant risk assessments, and other related analyses are in general methodologies that are well-known and accepted. The final results are determined not only by the methodology, but also assumptions and weighting factors that are used by the analyst. Consequently, these tools, while requiring review and rigorous quality assurance practices, will not require the validation and development of the systems design and licensing tools.

### ***Fuel Development & Qualification***

Development and qualification of TRISO-coated LEU fuel is a key research and development activity associated with NGNP. Kernel fabrication, coating, compacting at commercial scale, and irradiation and accident testing are required to qualify TRISO-coated fuel. The ultimate goal of this R&D program is to successfully demonstrate that TRISO-coated fuel can withstand the high-temperatures, high-burnup and radionuclide confinement requirements of the NGNP. In addition, the commercialization of the fuel fabrication process to achieve a cost-competitive TRISO-coated particle fuel manufacturing capability to reduce entry-level risks represents a primary goal for the fuel program. The NGNP Fuel Development and Qualification Program consists of five elements: (a) Fuel Manufacture—the work necessary to produce coated-particle fuel that meets fuel performance specifications and includes process development for kernels,

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<sup>14</sup> Fuel behavior codes are covered under the Fuel Development and Qualification effort.

coatings, and compacting; quality control (QC) methods development; scale-up analyses; and process documentation needed for technology transfer. (b) Fuel and Materials Irradiations – Data on fuel performance under irradiation will be obtained as necessary to support fuel process development, to qualify fuel for normal operation conditions, and to support development and validation of fuel performance and fission product transport models and codes. The irradiations will also provide irradiated fuel and materials as necessary for post irradiation examination (PIE) and ex-core high-temperature furnace safety testing. A total of eight irradiation capsules will be used to provide the necessary data and sample materials. (c) Safety Testing and PIE – Data from PIE and safety testing will supplement the in-reactor measurements as necessary to demonstrate compliance with fuel performance requirements and support the development and validation of computer codes. This work will also support the fuel manufacture effort by providing feedback on the performance of kernels, coatings, and compacts. (d) Fuel Performance Modeling – Computer codes and models will be further developed and validated as necessary to support fuel fabrication process development and plant design and licensing. The fuel performance modeling will address the structural, thermal, and chemical processes that can lead to coated-particle failures. The models will not address the release of fission products from the fuel particle, although they will model the effects of fission product chemical interactions with the coatings, which can lead to degradation of the coated-particle properties. (e) Fission Product Transport and Source Term – The transport of fission products produced within the coated particles will be modeled to provide a technical basis for source terms for advanced gas reactors under normal and accident conditions. The design methods (computer models) will be validated by experimental data, as necessary to support plant design and licensing.

### ***Materials & Components***

The NGNP Reactor Materials Program will provide the essential materials selection and qualification activities needed to support the design of the reactor and balance of plant. The NGNP materials program will perform all material identification, selection, testing, and qualification activities required to support the NGNP Reactor Project, as follows: (a) Development of a specific program plan for managing the selection and qualification of all component materials, (b) Identification of specific materials for each system component, (c) Evaluation of the needed testing, ASME Boiler and Pressure Vessel code work, and analysis required to qualify each identified material, (d) Preliminary down-selection of component materials based on known requirements, (e) Specification and purchase of representative materials for testing, (f) Design/construction of capsules and vehicles for irradiation of materials where irradiation test data is required, (g) Performing irradiation of needed sample materials, (h) Physical, mechanical, and chemical testing of irradiated and un-irradiated materials as required to provide the data to qualify the material for the specific components, (i) Documentation of materials test data, (j) Documentation of final materials selections.

The materials program will address the NGNP reactor, power conversion system, intermediate heat exchange (IHX) system, and associated balance of plant. Inclusion of materials for hydrogen production will be determined later. As an integral part of the reactor project, the NGNP materials program must interface directly with the reactor design and component specification efforts in an iterative process of component requirements refinement and materials applicability considerations leading to final selection of needed materials.

## ***Hydrogen Production***

The R&D strategy for hydrogen production technologies is focused on the following three key areas of development: (a) S-I Process Development –The most promising methods using nuclear energy are based on electrolytic or thermochemical processes. (b) Technology Assessment – The primary issue for nuclear hydrogen is the development of systems that produce hydrogen at a cost that is competitive with gasoline. The criteria to be used to evaluate the benefits of the various hydrogen production methods to meet these cost objectives include the system and performance characteristics that drive costs, and the uncertainty of those costs. (c) Process Demonstration Strategy – Demonstrating nuclear hydrogen production by 2016 will require that candidate process information be sufficiently complete to provide an adequate basis for decisions on the next stage of demonstration. Baseline processes are closer to demonstration than are the alternative processes. However, all potential processes will develop in a similar sequence, beginning with the demonstration of viability on a laboratory-scale.

## ***Power Conversion & High Performance Helium Turbine***

The pre-conceptual design, proposal, design selection, design implementation, and manufacturing of the required high performance helium turbine(s) are activities that must be centered on the selection and interaction with a qualified manufacturer. Until the design is completed, INEEL researchers can model the presence of the required turbine using assumptions based on the system design specifications. A detailed High Performance Turbine R&D Plan will be developed during the Project Initiation Phase that will provide a breakdown of activities, cost and schedule for this area of NGNP R&D work.

## ***Ten Year Plan***

The top level objectives of the R&D plan over the period FY04 through FY13 are:

- Complete conceptual design
- Complete NEPA and EA process
- Complete Project Execution Plan
- Complete Preliminary Design
- Issue Final Materials Qualification Selection Documents for selected components
- Manufacture qualification fuel and initiate fuel qualification irradiation
- Complete Final Design
- Complete NRC Permit to Construct

Table 5.1.1 shows the funding projection for the NGNP and Table 5.1.2 shows the projected costs for NGNP Hydrogen Plant Development.

**Table 5.1.1** Projected NGNP R&D and Reactor Plant Costs, FY04 through FY13 (\$M)

Program		FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	Total FY04- 17
Research & Development	Materials & Turbine Development	0.7	15.7	44.5	46.8	46.1	30.1	18.0	5.3	2.4	2.2	218.4
	Fuel Development	4.5	17.0	17.6	13.5	14.6	15.7	13.6	13.0	13.0	10.3	195.8
	Confirmatory Development	0	9.4	13.9	17.4	12.9	7.9	2.8	0	0	0	64.3
R&D Total		5.2	42.1	76.0	77.7	73.6	53.7	34.4	18.3	15.4	12.5	478.5
NGNP Reactor & Plant	Reactor & Plant Design	8.2	12.9	19.2	22.6	40.6	42.2	41.8	42.9	0	0	230.4
	Plant Equipment & Construction	0	0	0	0	0	41.5	49.4	52.7	105.6	106.2	668.9
	Licensing, EIS, & Permitting	0	4.4	5.9	7.6	10.5	9.1	5.4	3.2	7.5	9.0	91.6
NGNP Reactor & Plant Total		8.2	17.3	25.1	30.2	55.8	91.2	98.5	139.0	135.1	118.8	990.8
NGNP Reactor and R&D		<b>13.4</b>	<b>59.4</b>	<b>101.1</b>	<b>107.9</b>	<b>124.7</b>	<b>146.5</b>	<b>131.0</b>	<b>117.1</b>	<b>128.5</b>	<b>127.7</b>	<b>1469.3</b>

**Table 5.1.2** Projected NGNP Hydrogen Plant Development Costs, FY04 through FY13 (\$M)

Program	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	Total FY04- 17
Lab-Scale	6.2	8.1	8.1	17.6	9.9	5.0	9.5	0.5	0	0	56.8
Pilot Plants	0.3	0.9	3.4	14.1	19.1	14.5	25.0	16.6	9.1	0	103.0
Engineering Scale Demo	0	0	0	1.0	1.0	1.0	4.5	13.4	25.9	40.0	238.4
Total	<b>6.5</b>	<b>9.0</b>	<b>21.0</b>	<b>25.0</b>	<b>25.1</b>	<b>25.0</b>	<b>30.0</b>	<b>30.0</b>	<b>35.0</b>	<b>40.0</b>	<b>398.2</b>

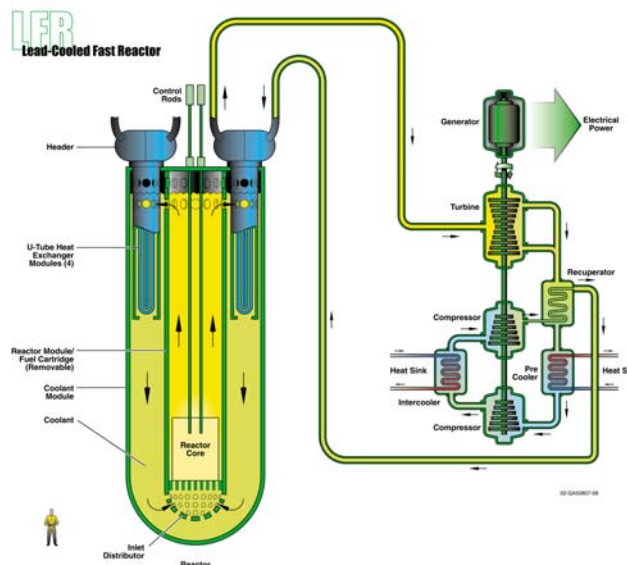
**Major Milestones**

- FY04:**
1. Issue the System Design and Evaluation Methods research and development plan.
  2. Award contract for pre-conceptual design of the NGNP.
  3. Issue Requirements for Material Selection and Qualification Program Plan.
  4. Complete draft Materials Quality Assurance Plan.
  5. Complete irradiation and storage of graphite scoping capsules.
  6. Complete draft Project Quality Assurance Plan.
  7. Submit updated draft NGNP Program Plan approximately two months after RFP issue.
  8. Issue the final Independent Technical Review Group Report.
- FY05:**
1. Complete preconceptual design studies.
  2. Initiate Environmental Impact Statement.
  3. Issue Materials Qualification Testing Program Plan.
  4. Complete fabrication and assembly for AGR-1 experiment.
  5. Fabricate LEU UCO kernels for AGR-2, 3, 4.
  6. Select thermal-hydraulic and neutronic tools for NGNP analysis.

- FY06:** 1. Complete Conceptual Design F&ORs  
2. Complete 6" Coater scale-up Design and Testing  
3. Define the experimental needs to enable the NGNP tools to be qualified.  
4. Complete Phase I experimental program for NGNP.
- FY07:** 1. Complete conceptual design.  
2. Complete Project Execution Plan.  
3. Finalize acquisition strategy.  
4. Initiate NRC Pre-licensing process.  
5. Issue Final Materials Qualification Selection Documents for selected components.
- FY08:** 1. Complete NEPA and EA process.  
2. Issue Final Materials Qualification Selection Documents for selected components.  
3. Perform calculations for PSAR.
- FY09:** 1. Complete Preliminary Design.  
2. Complete Independent Cost Estimate.  
3. Manufacture qualification fuel and initiate fuel qualification irradiation.  
4. Issue Final Materials Qualification Selection Documents for selected components.
- FY10:** 1. Initiate long lead equipment procurement (e.g. IHX, vessels).  
2. Begin Irradiation of AGR-4.  
3. Complete integral experiments to satisfy NGNP V&V requirements.
- FY11:** 1. Complete Final Design.  
2. Complete NRC Permit to Construct.  
3. Complete Phase I final audit calculations of NGNP design.
- FY12:** 1. Start Construction.  
2. Initiate Final Safety Analysis Report.  
3. Complete Phase II final audit calculations of NGNP design.
- FY13:** 1. Issue ASME Codes and Standards Materials Development Progress Report.  
2. Complete Phase III final audit calculations of NGNP design.

## 5.2 Lead-Cooled Fast Reactor (LFR)

The desired outcome of this program will be a lead or lead bismuth eutectic (LBE) cooled fast reactor (LFR) design, of relatively small size (10 to 100MWe), developed through demonstration by about 2025, such that the system is prepared for commercialization (see Figure 5.2). It is envisioned as a small, factory-built turnkey plant having a closed fuel cycle with a very long refueling interval (15 to 30 years) cassette core or sealed, replaceable reactor module that is capable of autonomous load-following allowed by inherent safety features. The reactor would be designed to meet market opportunities for electricity production on small grids, and for developing countries that may not wish to deploy an indigenous fuel cycle infrastructure. It may also be designed for the production of hydrogen using high-temperature processes. The reactor will accommodate a closed fuel cycle while ensuring substantial proliferation resistance by limiting access to fuel and associated fuel handling infrastructure.



**Figure 5.2** Lead-Cooled Fast Reactor

The R&D activities envisioned for this project include those related to reactor design, fuels, materials and addressing institutional and deployment issues. In addition, the anticipated collaboration and coordination with ongoing related activities in Japan can be considered to be an important adjunct to these efforts.

### *System Design & Evaluation*

System design and evaluation activities will address issues related to reactor design, energy conversion, instrumentation and control, and modular manufacturing and transportation. The design work will include pre-conceptual and conceptual design, trade studies to refine the reference design, research and development of necessary technology, and design of a demonstration prototype unit.

The objectives of the pre-conceptual studies, which are to be completed in FY-04, are to obtain a simplified design for a commercial plant to be deployed after the reactor systems are demonstrated. These design studies will consist of preliminary trade-off and simplified design studies. A major objective will be to obtain data to allow for incorporation of fuels and materials considerations into the pre-conceptual design used as a basis for the mission needs analysis. Another major objective is to define the functions and requirements for a demonstration plant to verify the innovative attributes that can be later incorporated into a commercial plant design.

The objective of the pre-conceptual design activities is to perform core physics design, thermal hydraulic design, and reactor systems design to develop a pre-conceptual design for a

demonstration test facility that will meet functions and requirements identified in the pre-conceptual studies. Core reactor physics design studies will determine core dimensions, fuel composition and loadings, and a reactivity control strategy for startup and autonomous load following. Thermal hydraulic design studies will determine the reactor system configuration and dimensions to achieve full natural circulation heat transport of the core heat rating together with autonomous load following and passive safety. Reactor and system designs will be developed for refueling/reload and logistics, balance of plant (i.e., Rankine steam cycle, supercritical steam cycle, or supercritical CO<sub>2</sub> Brayton cycle), mechanical design of key components including identification of materials for the components, seismic accommodation, design to achieve the core radial expansion behavior required for autonomous load following and strategies for decay heat removal.

The objective of the conceptual design effort is to perform the core design, safety evaluation, and reactor and plant conceptual design activities necessary to develop a conceptual design for the demonstration test facility. Core design activities will include core reactivity control concepts, operational evaluation, core mechanical design, core thermal hydraulic design, and assessment of core reactor physics performance and reactivity feedbacks. Safety evaluation will address implications of the reactivity feedback coefficients, system response to off-normal events, and seismic response evaluation. Reactor and plant conceptual design will encompass mechanical design of key components, design for radial expansion to achieve autonomous load following and passive safety, refueling/reload schemes and logistics, structural design features, decay heat removal schemes, containment approval, and the plant layout including power conversion.

## ***Fuels***

Key to this program is the identification of fuel and cladding materials and the design of the fuel system for the very long lifetime demanded by the LFR system. Therefore, the LFR program will address fuel development and testing as well as the back end of the fuel cycle. The near-term research in this effort will include defining fuel performance requirements, fuels design and definition, compatibility testing of fuel and cladding and their compatibility with lead coolant, selection of a reference fuel form and cladding material, cladding and coolant materials testing, and fuel design for long life.

Initial fuels work will be directed toward developing detailed fuel performance requirements based on the needs identified in the initial reactor design. These requirements will be updated as the design evolves from pre-conceptual to conceptual stages. In addition, a fuel qualification plan will be developed to address the needs of the reactor design and its safety and licensing approach. This plan will be complicated by limited availability of fast-spectrum testing facilities, so the start-up strategy for a demonstration plant will likely include provision for fuel performance verification and surveillance. Research and development work in the laboratory will focus on assessing the compatibility of fuel and cladding candidates with lead coolant.

In addition to fuel design for reactor performance, fuel cycle issues will also be addressed in this program. It is important to ensure that the reference fuel design is compatible with the front and back end of the fuel cycle. Studies and analyses are planned to address availability of fuel

material and enrichment and to ensure fuel type compatibility with the reprocessing, partitioning and waste disposal options for final disposition.

### ***Materials and Coolant Technology***

The objectives of the LFR materials and coolant technology research are to identify materials of construction for a demonstration prototype reactor and for a commercially deployable design, to understand the technology required to ensure acceptable performance of lead coolants, and to provide the data required to support materials qualification in licensed reactor facilities. These objectives require the program to address significant materials and coolant technology challenges. These issues include:

- Corrosion challenges related to the use of lead coolants
- Monitoring and control of coolant flow and chemistry
- The need for a simple, low-maintenance design with high inherent safety to achieve high component reliability requirements
- High radiation damage performance requirements related to the fast neutron spectrum and the very long life time requirements
- Long cladding lifetime required for the long core life of the reactor
- High-temperature materials performance requirements

These issues, combined with the desire for an early demonstration prototype, result in significant materials science challenges. A systematic program of materials evaluation, research, development, and demonstration is planned to address these challenges in parallel with reactor and fuel development and demonstration. The approach includes early identification of leading candidate materials for critical applications, performing material testing and model development to provide a basis for construction of the prototype reactor where material performance can be confirmed, while pursuing one or more material options as a backup in the event the candidate fails to perform as needed. Materials to be considered early in the program are those used most recently in U.S. and non-U.S. fast reactor development programs and variants of those materials subsequently developed for lead alloy compatibility. Other materials to be considered include advanced ceramics, surface plating, and advanced composites that have been subject to development and investigation in other technologies, such as fusion energy and advanced turbines. Coolant technology activities will focus on developing instruments and sensors to measure coolant flow and chemistry. Techniques to control coolant chemistry, particularly oxygen and polonium contents will be developed.

### ***Institutional and deployment issues***

The institutional and deployment issues to be addressed will entail assessment of economic and proliferation resistance requirements, systems studies and other similar activities in support of the U.S. DOE project decision process, and safety and licensing activities to meet USNRC requirements. Work in this area will include specific activities needed to meet Critical Decision-0 (i.e., establishment of mission need) and Critical Decision-1 (i.e., conceptual

design) requirements. As part of this, the technical functions and requirements will be determined and refined. Another important element is economic and market analyses, which will provide economic performance requirements for the LFR. The safety and licensing approach will rely on a license-by-test strategy, but this strategy must be formulated in collaboration with appropriate offices of the U.S. Nuclear Regulatory Commission. Issues related to siting, manufacturing, installation and unit replacement will also be identified and addressed.

International collaboration is an important consideration. This involves potential technical collaboration with other national programs addressing small, fast spectrum reactors or related technologies, including activities coordinated through the Generation IV International Forum. In addition, the joint US-Japan collaboration on small, fast reactors is and will be a continuing cornerstone of this program. Japanese programs, especially those related to the CRIEPI/Toshiba Super Safe Small and Simple (4S) reactor design, have demonstrated that nation's longstanding interest and commitment to small, fast reactors. During the past year, a joint project entitled the Joint Preliminary Feasibility Study (JPFS) has been carried out with participants from CRIEPI, LLNL and ANL. The purpose of JPFS has been to evaluate the 4S design in three major areas: International Security, Market and Economics and Safety. The study suggests R&D and potential design modifications needed to make the program suitable as a joint U.S.-Japan effort and it evaluates possible design certification by the U.S.-NRC. Reconciliation of Japanese design objectives with those of the U.S. LFR program will initially be accomplished through collaborative evaluation of design options and negotiation. Successful implementation of a government-to-government agreement will lead to an integrated program of research, development and demonstration beginning in the FY05-06 time frame.

### ***Ten-Year Plan***

The high-level objectives of the LFR R&D program within the AFC and Generation IV programs are to:

- Prepare, assess and optimize small, modular LFR designs
- Establish the proliferation resistance attributes of the system, the *license-by-test* approach, and the economic requirements for selected deployment scenarios
- Establish potential of candidate LFR cladding and structural materials
- Establish potential fuels and fuel cycles
- Establish potential to couple the LFR with energy conversion devices
- Interface with GIF to optimize effectiveness of the R&D plan
- Determine the viability of an early deployment option

Table 5.2.1 shows the projected R&D costs.

**Table 5.2.1 Projected R&D Costs for the LFR (\$K)**

<b>Technology</b>	<b>FY 04</b>	<b>FY05</b>	<b>FY06</b>	<b>FY07</b>	<b>FY 08</b>	<b>FY 09</b>	<b>FY 10</b>	<b>TOTAL</b>
System Design & Evaluation	540	450	1500	1500	1500	1500	2800	9790
Materials	460	350	2000	2000	2000	2000	1200	10,010
Energy Conversion	0	0	500	500	500	500	0	2,000
Fuels & Licensing	0	0	1500	1500	2000	2000	1200	8,200
<b>Total</b>	<b>1000</b>	<b>800</b>	<b>5500</b>	<b>5500</b>	<b>6000</b>	<b>6000</b>	<b>5200</b>	<b>30,000</b>

***Major Milestones*****FY04:** 1. Issue LFR 10-Year <sub>Program</sub> Plan Draft.

2. Issue Licensing and Safety Approach Report.

3. Issue report on DELTA experiments, operation and corrosion test results.

**FY05:** 1. Establish point design for subsequent concept development.

2. Issue document of economic requirements and proliferation-resistance principles.

**FY06:** 1. Issues design and <sub>data</sub> needs document.

2. Issue fuel qualification strategy document.

**FY07:** 1. Issue report on SCO<sub>2</sub> design requirement for LFR.

2. Submit concept paper on implementation of fuel cycle centers.

**FY08:** 1. Establish techniques for lead/LBE chemistry control and flow measurement.

2. Establish reference fuel &amp; cladding type and design for long core lifetime.

**FY09:** 1. Complete initial measurements of natural flow properties for lead/LBE.

2. Issue report on lead/LBE corrosion behavior of LFR materials candidates.

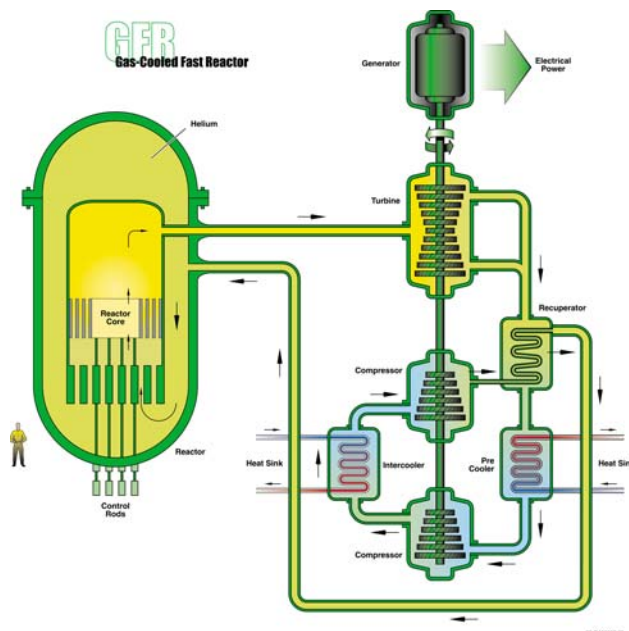
**FY10:** 1. Establish pre-conceptual design.**FY11:** 1. Issue report on status of mechanistic materials modeling.

2. Issue report on irradiation performance of LFR candidate materials.

**FY12:** 1. Establish reference core design parameters.**FY13:** 1. Submit status report on LFR conceptual design.

### 5.3 Gas-Cooled Fast Reactor (GFR)

The gas-cooled fast reactor (GFR) system features a fast-spectrum helium-cooled reactor and closed fuel cycle (see Figure 5.3). Like thermal-spectrum helium-cooled reactors such as the Gas-Turbine Modular Helium Reactor (GT-MHR) and the Pebble Bed Modular Reactor (PBMR), the high outlet temperature of the helium coolant makes it possible to produce electricity, hydrogen or process heat with high conversion efficiency. The GFR uses a direct-cycle helium turbine for electricity (42% efficiency at 850°C), and process heat for thermochemical production of hydrogen. Optional coolants (e.g., supercritical CO<sub>2</sub>) may offer higher thermal efficiency (45%) using a direct-cycle, while maintaining lower coolant temperatures (at 550°C). The GFR's fast spectrum makes it possible to utilize available fissile and fertile materials (including depleted uranium from enrichment plants) several orders of magnitude more efficiently than thermal spectrum gas reactors with once-through fuel cycles. Furthermore, through the combination of a fast neutron spectrum and full recycle of actinides, GFRs minimize the production of long-lived radioactive waste isotopes, and can be designed for minor actinide management from spent fuel. The GFR system includes an integrated, on-site spent fuel treatment and refabrication plant.



**Figure 5.3** Gas-Cooled Fast Reactor

The needs for the GFR are being addressed in four areas: System Design & Evaluation, Materials, Power Conversion, and Fuels & Fuel Cycle. Each of these areas is briefly discussed.

The needs for the GFR are being addressed in four areas: System Design & Evaluation, Materials, Power Conversion, and Fuels & Fuel Cycle. Each of these areas is briefly discussed.

#### ***System Design & Evaluation***

Four major activities within the System Design and Evaluation activity will need to be pursued. These include safety system design and evaluation of passive and active safety systems for decay heat removal; system control and transient analysis; design and construction of experiments for thermal-hydraulic/safety tests, and coolant chemistry control; and code development/adaptation for neutronic and thermal-hydraulic analysis.

Safety system design and evaluation of passive/active safety systems for decay heat removal R&D includes the optimization of safety systems for decay heat removal (short, intermediate, and long term), including physics and thermal-hydraulic analyses for the reference and optional systems. Current studies show that a passive decay heat removal system is possible through heavy gas injection (i.e., using accumulators containing nitrogen or carbon dioxide), but may be further enhanced by coupling to an active system. Optimization studies will include containment

building design and performance, as natural convective (passive) cooling will require a pressurized containment.

As this reactor will use a direct-cycle for power conversion, reactor control issues will need to be identified and analyzed; this includes accident scenarios such as ATWS events, and the reactor's ability to shutdown passively through negative reactivity coefficients (e.g., expansion, etc.). Initiators for other transient events will also be identified through a limited scope PRA.

Heated loop, volume, and other experiments will be designed and constructed that can operate with high temperature helium (850°C) or high pressure CO<sub>2</sub> (20 MPa, 550°C), and will be used to: measure the pressure drop, measure heat transfer coefficients, perform passive safety experiments (e.g., containment response), and develop coolant monitoring techniques and chemistry control at prototypical GFR operating conditions. Simulation of various core geometries will be possible including block, pin, plate, and/or pebble cores.

Adaptation of existing calculational tools to support system design, development and safety evaluations of the GFR will be performed. Neutronics and thermal-hydraulics tools will be the focus. Future activities will focus on verification and validation. This activity will be planned, coordinated, and executed as a Methods Development and Evaluation crosscut activity.

### ***Materials***

Two major activities within the Materials area will need to be pursued. These include screening and testing of high temperature materials and corrosion studies using supercritical CO<sub>2</sub>.

Screening and testing of candidate high temperature materials will be performed, including fabricability and survivability testing. Leading in-core and out-of-core candidates will then be tested appropriately (e.g., in-core materials will be tested in-pile for irradiation damage).

Screening of potential/candidate materials for in-core and ex-core service will be performed, where high pressure and medium temperatures will be used during the tests. In addition, radiolysis experiments will be performed to identify the chemical species that are formed in the CO<sub>2</sub> coolant during irradiation.

### ***Power Conversion***

Two major activities within the Power Conversion area will need to be pursued. These include feasibility studies of a direct Brayton cycle and development of the turbomachinery for helium and CO<sub>2</sub> systems. These activities have been identified as crosscutting, and will be planned, coordinated, and executed under the Power Conversion crosscut area.

Feasibility issues regarding demonstration of the Brayton cycle for both helium and supercritical CO<sub>2</sub> will be studied, including single shaft or multi-shaft systems. Some of these issues can be resolved with an integral test facility, and/or small-scale component demonstrations.

Turbine, compressor, and other component design will be initiated with special attention being paid to the turbine design. Performance will be assessed, as well as optimization. This activity will be closely coupled to the balance-of-plant activity.

## ***Fuels & Fuel Cycle***

Three major activities within the Fuels and Fuel Cycle activity area will need to be pursued. These are fuels feasibility, fabrication, and testing; recycle process feasibility studies; and studies on the viability of refabrication. These activities are summarized below, and will be closely coordinated with the Advanced Fuel Cycle Initiative work.

Fuel survivability in high temperature/high fluence environments, and coolant/fuel incompatibilities for medium temperature fuels, will be assessed (including carbide, nitride, oxide, and metallic fuels). Comparisons of benefits/challenges of each fuel type will be performed. Special attention will be paid to those fuels that may be able to support large fractions of minor actinides.

While fabrication of oxide and metallic fuels is fairly well understood, both carbide and nitride fuel forms require development. Economic fabrication techniques will be sought, as well as appropriate matrix materials for dispersion fuels. Irradiation testing of fuels containing minor actinides will also be performed.

Recyclability of candidate fuels and matrix materials will be assessed, which will include possible use of current technologies (e.g., pyro, aqueous, and/or other dry processes). For those fuel forms that are beyond current technologies, new processes will be evaluated for both technical and economical viability.

Equilibrium and heavy minor actinide bearing fuels will be tested for refabricability (i.e., remote fabrication techniques will be selected and tested). The closed fuel cycle will be tested through irradiation and processing of the candidate fuels.

## ***Seven-Year Plan***

The overall objectives during the seven-year performance period are to select a credible core design with excellent safety characteristics, assess the viability of candidate fuels and materials that are able to withstand prototypical GFR environments, develop and test balance-of-plant components to confirm the viability of direct (and indirect) power conversion cycles, and screen/develop economical recycle processes for the reference fuels. Activities integral to those mentioned above will also consist of pre-conceptual designs that are inclusive of fuels containing high minor actinide concentrations for spent fuel waste management. These objectives are consistent with the estimated required budget levels shown in Table 5.3.1.

**Table 5.3.1. Required seven-year budget profile for GFR activities (\$K).**

<b>Technology</b>	<b>FY 04</b>	<b>FY05</b>	<b>FY06</b>	<b>FY07</b>	<b>FY 08</b>	<b>FY 09</b>	<b>FY 10</b>	<b>TOTAL</b>
System Design & Evaluation	150	300	2000	1500	1500	1500	2800	9750
Materials	0	0	1500	2000	2000	2000	1200	8,700
Energy Conversion	0	0	0	0	500	500	500	1,500
Fuels & Fuel Cycle	250	200	2000	2000	2000	2000	1400	9,850
<b>Total</b>	<b>400</b>	<b>500</b>	<b>5500</b>	<b>5500</b>	<b>6000</b>	<b>6000</b>	<b>5900</b>	<b>29,800</b>

## Major Milestones

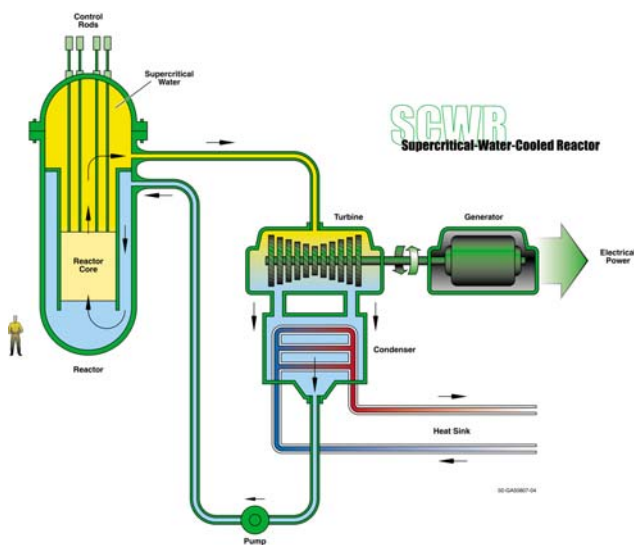
**FY06:** Initiate a GFR fuel irradiation program.

**FY07:** Complete basic GFR core design and systems safety analysis sufficient to support design safety goals.

**FY08:** Complete first phase of advanced GFR fuel irradiation, and select the safety system(s) to finalized pre-conceptual design.

**FY10:** Finalize pre-conceptual design in sufficient detail to permit a comparison with the other two fast reactor technologies, on economics, proliferation resistance, safety and licensing, and sustainability.

## 5.4 Supercritical Water-Cooled Reactor (SCWR)



**Figure 5.4** Supercritical Water-Cooled Reactor

Supercritical water-cooled reactors (SCWRs) are promising advanced nuclear systems because of their high thermal efficiency (i.e., about 45% vs. about 33% efficiency for current Light Water Reactors, LWRs) and considerable plant simplification (see Figure 5.4). SCWRs are basically LWRs operating at higher pressure and temperatures with a direct once-through cycle. Operation above the critical pressure eliminates coolant boiling, so the coolant remains single-phase throughout the system. Thus the need for recirculation and jet pumps, pressurizer, steam generators, steam separators and dryers is eliminated. The main mission of the SCWR is generation of low-cost electricity. It is built upon two proven technologies, LWRs, which are the most commonly deployed power generating reactors

in the world, and supercritical fossil-fired boilers, a large number of which is also in use around the world. The SCWR concept is being investigated by 32 organizations in 13 countries. In the U.S. the Generation-IV SCWR program operates under the following general assumptions, which are consistent with the SCWR's focus on electricity generation at low capital and operating costs:

- ◆ Direct cycle,
- ◆ Thermal spectrum,
- ◆ Light-water coolant and moderator,
- ◆ Low-enriched uranium oxide fuel,
- ◆ Base load operation.

The Generation-IV International Forum (GIF) SCWR Steering Committee has generated a schedule for the demonstration of the SCWR concept that call for the completion of all essential R&D by 2015 and construction of a small-size ( $\leq 150$  MWt) prototype SCWR by 2020.

The objective of the 10-year plan is to assess the technical feasibility of the SCWR concept. Therefore, the plan focuses on the two key feasibility issues that were identified in the Generation IV Roadmap Report for this concept, i.e., selection/development of structural materials, and demonstration of adequate safety and stability. Issues like economic evaluation, detailed design and materials codification are deemed of secondary importance at this point, and thus are not addressed.

### ***System Design & Evaluation***

It is envisioned that the first phase of the Gen-IV R&D program for SCWR will focus on demonstrating the technical feasibility of the concept. This phase will address five critical issues as identified in the Generation-IV Roadmap report:

- 1) Establish a baseline design for the SCWR core and reactor coolant system,
- 2) Generate basic data on heat transfer, pressure drop and critical flow for supercritical water at SCWR prototypical conditions,
- 3) Identify suitable safety systems and containment designs to cope with the consequences of major abnormal events,
- 4) Evaluate the susceptibility of the SCWR to thermal-hydraulic and coupled thermal-hydraulic/neutronic instabilities,
- 5) Develop a strategy for reactor control including start-up and operational transients.

Activities under in this functional area include SCWR core and safety system design, evaluation of the system susceptibility to power-flow instabilities, start-up and control of the main reactor variables, and expansion of the heat-transfer database at prototypical SCWR flow conditions.

A conceptual design of the SCWR core and balance-of-plant (BOP) will include development of a credible fuel assembly design to provide adequate moderation in the core, development of a reactivity control system based on control rods and burnable poisons, and the design of a suitable power conversion cycle.

Experiments are needed in a versatile, electrically heated, forced-circulation loop to confirm or develop mathematical models for heat transfer and pressure drop through near-prototypical SCWR geometries. These models will be required in the computer codes used to assess and evaluate design options.

A design strategy to ensure safety will be developed to cope with postulated sequences. This task will mostly focus on assessing the applicability to the SCWR of active and passive safety systems developed for advanced LWRs (e.g., ESBWR, AP-600) including isolation condensers, gravity-driven cooling systems and a passive containment cooling system.

A design issue that must be studied and understood is the susceptibility of the SCWR to instability phenomena. Analytical models will be used to predict the onset of instability of the density-wave, coupled thermal-hydraulic/neutronic and natural-circulation type, at nominal, start-up and overpower conditions. Supporting experiments will also be performed.

A design strategy will be developed to control the main reactor variables, e.g., core power, coolant pressure and temperature, as well as methods for plant start-up from cold conditions.

### ***Materials***

Key issues regarding the feasibility of materials for the SCWR cladding and core internals will be evaluated with ex-pile and in-pile experiments: general corrosion, stress-corrosion cracking, radiation effects on coolant chemistry and on materials mechanical properties, and microstability.

Materials to be used for cladding and core structures will be screened for compatibility with the supercritical water environment. Corrosion testing of potential materials will be undertaken as a function of temperature, dissolved gasses, and water chemistry.

Stress corrosion cracking (SCC) testing of potential materials will be conducted with a controlled-strain machine. Testing of proton-irradiated samples will allow evaluation of the effects of irradiation damage.

Dimensional and microstructural stability studies of irradiated materials will be focused on obtaining information on the structural effects of irradiation as a function of dose and temperature. The information will be obtained from proton-irradiated materials examined in cold laboratories as well as from neutron-irradiated materials in hot cells.

Tests will be conducted to obtain information on material tensile properties, creep rates, creep rupture mechanisms, creep-fatigue, time dependence of plasticity and high temperature plasticity, fracture toughness, ductile-to-brittle transition temperature and helium embrittlement. The research program will be aimed at high temperature performance of both irradiated and un-irradiated alloys and also at low temperature performance of irradiated alloys.

### ***Ten-Year Plan***

The objective of the ten-year plan is to assess the technical feasibility of the SCWR concept. The plan focuses on the key issues of identifying suitable core materials and demonstrating adequate safety and stability. The plan calls for both experimental and analytical work to be performed by national labs, universities and industry. Table 5.4.1 shows the required funding levels.

**Table 5.4.1** Required SCWR Budget (\$K)

Functional Area	Task	FY-04	FY-05	FY-06	FY-07	FY-08	FY-09	FY-10	FY-11	FY-12	FY-13	Total
<b>System Design</b>	Core and Reactor Coolant System Design	0	0	300	1000	1500	1500	1000	1000	1000	500	7800
	Basic Thermal Data	0	250	1400	300	300	300	300	200	200	200	3450
	Safety System and Containment	150	150	200	400	500	500	500	400	300	200	3300
	Stability	200	0	500	500	400	300	300	0	0	0	2200
	Control and Start-up	60	0	200	200	200	0	0	0	0	0	660
	<b>Total</b>	<b>410</b>	<b>400</b>	<b>2600</b>	<b>2400</b>	<b>2900</b>	<b>2600</b>	<b>2100</b>	<b>1600</b>	<b>1500</b>	<b>900</b>	<b>17410</b>
<b>Materials</b>	RPV	0	0	150	330	440	440	500	470	200	20	2550
	RPV Internals	380	300	500	1400	2100	1800	4000	5000	4200	3000	22680
	Pumps and Pipes	0	0	400	380	1000	1560	1280	1160	840	640	7260
	Power Conversion Cycle	0	0	0	60	820	1000	920	60	60	20	2940
	<b>Total</b>	<b>380</b>	<b>300</b>	<b>1050</b>	<b>2170</b>	<b>4360</b>	<b>4800</b>	<b>6700</b>	<b>6690</b>	<b>5300</b>	<b>3680</b>	<b>35430</b>
<b>Program Management</b>		<b>110</b>	<b>100</b>	<b>130</b>	<b>300</b>	<b>500</b>	<b>500</b>	<b>500</b>	<b>500</b>	<b>500</b>	<b>400</b>	<b>3540</b>
<b>Grand-total</b>		<b>900</b>	<b>800</b>	<b>3780</b>	<b>4870</b>	<b>7760</b>	<b>7900</b>	<b>9300</b>	<b>8790</b>	<b>7300</b>	<b>4980</b>	<b>56380</b>

**Major Milestones:**

**FY04:** 1. Identify and evaluate suitable safety systems for the total loss of feedwater transient.  
2. Perform a pre-conceptual design of the coolant chemistry control strategy.

**FY05:** 1. Complete pre-conceptual design of ECCS and containment.

**FY06:** 1. Complete construction of the heat transfer facility.  
2. Complete pre-conceptual design of the core and vessel internals.

**FY08:** 1. Complete conceptual design of control and start-up systems.  
2. Complete corrosion and SCC screening tests of unirradiated materials in supercritical water.

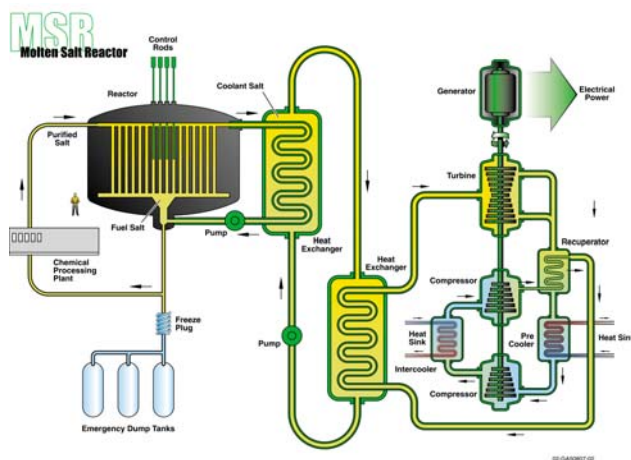
**FY10:** 1. Complete SCW heat transfer experiments.  
2. Complete corrosion and SCC testing of primary candidate materials for core support components in supercritical water at simulated in-reactor chemistry.  
3. Complete stability analysis.

**FY11-13:** 1. Complete conceptual design of the SCWR including core, reactor coolant systems, safety systems, and containment.  
2. Complete demonstration of fabrication capability for RPV thickness.  
3. Complete irradiation of replaceable fuel assemble candidate materials with neutrons and protons.  
4. Complete post-irradiation mechanical properties testing, microstructural characterization of replaceable fuel assemble candidate materials.

5. Complete post-irradiation corrosion and IASCC testing in supercritical water testing of replaceable fuel assemble candidate materials.

### 5.5 Molten-Salt Cooled Reactor (MSR)

MSRs are liquid-fueled reactors that can be used for production of electricity, actinide burning, production of hydrogen, and production of fissile fuels (see Figure 5.5). Fissile, fertile, and fission products are dissolved in a high-temperature molten fluoride salt with a very high boiling point (1400°C) that is both the reactor fuel and the coolant. The use of liquid fuels presents some unique capabilities such as destruction of long-lived actinides without solid fuel fabrication, a wider choice of fuel cycles without major changes in the reactor design, and high temperature operation compatible with helium power conversion cycles. The reactor can be built in large sizes with passive safety systems. These unique capabilities however provide technical challenges, which differ from other Generation IV systems capable of actinide management.



**Figure 5.5** Molten Salt-Cooled Reactor

#### *Ten-Year Plan*

The high-level objectives of the MSR R&D program within the Generation IV programs are to:

- Establish a pre-conceptual point design for a modern economic MSR
- Assess tradeoffs between the reactor design and potential fuel cycle missions such as transmutation. Decisions for a second repository are likely to be made by 2009; thus, an understanding of these tradeoffs must be completed by 2007.
- Develop a cost estimate of a MSR. Economics is an absolute requirement for large scale deployment; thus, a preliminary understanding is required by 2010 when preliminary decisions on advanced reactors for fuel production are made.
- Establish potential of energy conversion systems to use molten salts as heat transfer agents and the ability to couple the MSR with energy conversion devices.
- Coordinate with ACFI Program to develop an integrated fuel cycle that couples with other reactors for actinide burning.
- Interface with Generation IV International Forum to optimize effectiveness of R&D plan

Major decisions (above) on the need for a second repository and down select of reactor options for fuel production divide the program into stages to support decisions. The activities for FY 2004 through FY 2013 are supported by funding as shown in Table 5.5.1.

**Table 5.5.1.** Cost estimate for required scope to conclude viability demonstration by 2010 and perform higher-priority R&D after technology selection (\$K).

Task	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	Total
Materials	0	0	800	1800	1500	1000					
Fuel and Fuel Cycle	0	40	1400	1000	500	500					
System Design and Evaluation	40	120	800	1000	2500	2500					
Energy Conversion	0	0	200	500		500					
<b>TOTAL</b>	<b>40</b>	<b>160</b>	<b>3200</b>	<b>4300</b>	<b>4500</b>	<b>4500</b>	<b>4000</b>	<b>4000</b>	<b>6000</b>	<b>6000</b>	<b>36700</b>

### Major Milestones

**FY04:** 1. Define key design features for a MSR (such as power cycle, etc.).

**FY06:** 1. Complete pre-conceptual design a modern MSR.

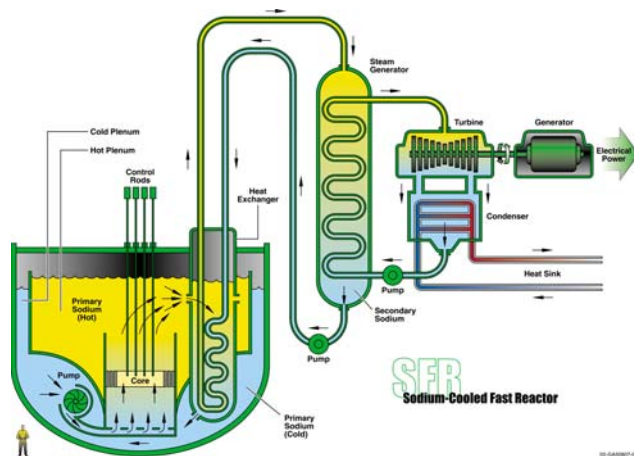
**FY07:** 1. Complete actinide burning assessment.

**FY08:** 1. Complete initial system safety study.  
2. Complete initial loop corrosion tests on new materials.

**FY09:** 1. Complete conceptual design, operations/maintenance, and costing study

**FY10:** 1. Develop integrated development and commercialization plan.

### 5.6 Sodium-Cooled Fast Reactor (SFR)



**Figure 5.6** Sodium-Cooled Fast Reactor

The sodium-cooled liquid metal reactor (SFR) system features a fast-spectrum reactor and closed fuel recycle system (see Figure 5.6). Plant size ranges from few hundred MWe modular system to large 1500-1700 MWe monolithic reactors. The primary mission for the SFR is the management of high-level wastes, and in particular, management of plutonium and other actinides. With innovations to reduce capital cost the mission can extend to electricity production, given the proven capability of SFR to utilize almost all of the energy in the natural uranium.

The R&D objectives for the SFR are

primarily related to the system design and safety:

- Identify plant cost reduction features, including potential development of advanced steam generator designs, and evaluate their feasibility and potential.
- Establish the technical basis for passive safety and understanding bounding accidents.
- Coordination with fuel and fuel cycle development and coordination of the R&D plan with Gen IV International Forum

The SFR has been significantly developed and may not require as much system design R&D as other Generation IV systems. R&D is nevertheless needed for demonstration of the design and safety characteristics, especially with fuels containing minor actinides, and to optimize the design with innovative approaches to meet the objectives of the specific missions of Generation IV, primarily actinide management.

### ***Ten-Year Plan***

The R&D objectives for the SFR under the Generation IV program are primarily related to the System Design and Safety:

- Identify plant cost reduction features, including potential development of advanced steam generator concepts, and evaluate their feasibility and potential.
- Establish the technical basis for passive safety and understanding bounding accidents.
  - Coordination of activities with AFCI, GIF, and crosscut R&D.

If the SFR technology were selected in FY2010, a design activity would be started in preparation for the construction phase. This is not included in the R&D needs identified here.

Funding to support the major deliverables is shown in Table 5.6.1.

**Table 5.6.1** Projected Costs for SFR R&D Activities, FY04-FY13 (\$K)

<b>Task</b>	<b>FY04</b>	<b>FY05</b>	<b>FY06</b>	<b>FY07</b>	<b>FY08</b>	<b>FY09</b>	<b>FY10</b>	<b>FY11</b>	<b>FY12</b>	<b>FY13</b>	<b>TOTAL</b>
System design and evaluation: experimental plan management	40	2540	1000	1000	1000	1000	1000				7580
Debris Coolability			500	500	1000	2000	1000				5000
In-vessel retention			500	500	500	500					2000
Recriticality prevention			500	1000	2000	2000	500				6000
Facilities			3000	2000	2000	1000					8000
ISI&R								2000	2000	2000	6000
Steam Generators								3000	3000	3000	9000
<b>TOTAL</b>	<b>40</b>	<b>2540</b>	<b>5500</b>	<b>5000</b>	<b>6500</b>	<b>6500</b>	<b>2500</b>	<b>5000</b>	<b>5000</b>	<b>5000</b>	<b>43580</b>

## ***Major Milestones***

- FY05:** 1. Report on identification of remaining viability R&D with emphasis on safety.
- FY06:** 1. Report on identification, feasibility and potential of SFR system cost reduction features.
- FY07:** 1. Issue program plans for: modeling and validation of passive safety for MA-bearing fuels and for the investigation of bounding events.
- FY08:** 1. Issue interim annual reports on: SFR R&D activities in safety and on cost reduction studies.
- FY09:** 1. Issue interim annual reports on: SFR R&D activities in safety and on cost reduction studies.
- FY10:** 1. Issue report on: Safety activities and experimental plan for transient tests of MA-bearing fuel, and on SFR viability R&D and proposed Performance R&D.

## **5.7 Design and Evaluation Methods Crosscut**

Design and Evaluation Methods Crosscut R&D is key to the development of Generation IV systems that meet performance goals. System-specific design R&D activities are described in previous sections. This section describes crosscutting design and evaluation R&D directed to (a) coordination of system design, analysis and evaluation activities across Generation IV systems, (b) development and qualification of crosscutting methods for design analysis of Generation IV systems, and (c) development of methodologies for evaluating overall system performance against Generation IV technology goals.

### ***Coordination of Design and Evaluation Methods R&D***

This task consists of two major activities. The first is to provide coordination of methods development, analysis and evaluation activities across Generation IV systems, taking advantage of relevant advances in methods development R&D in other national and international programs. The second major activity is to plan and oversee crosscutting methods development and evaluation R&D. This activity has the objectives of advancing capabilities for system analysis, supporting system design optimization, and providing capabilities to assess system performance against Generation IV goals.

### ***Improvement of Design and Safety Analysis Capabilities***

The design of Generation IV systems will rely extensively on advanced simulation capabilities to provide accurate predictions of system performance. Viability of innovative system design features will require confirmation by credible analyses verified with experimental data. Also, credible analyses will be required as the basis for regulatory reviews and licensing of Generation IV designs of choice. Crosscutting activities directed to enhancing design and safety analysis capabilities are expected to include computational fluid dynamics (CFD) simulations, system dynamic simulations, nuclear data, Monte Carlo analyses, neutronic design codes, and sensitivity analysis capabilities.

Although CFD has so far proven to be a useful design tool in many industrial applications its applicability for different types of coolants or for simulation of accident conditions remains to be established. Programs are needed that increase the accuracy of CFD, extend its range of applicability, and experimentally validate its predictions as an engineering simulation tool. The initial focus will be on verifying the applicability of commonly used CFD software for different types of coolants, distinct heat transfer regimes, and a wide range of flow phenomena.

A crosscutting systems dynamics tool for consistent assessment of designs is needed. A planned activity is the evaluation, enhancement, and integration of modules from various system dynamics code versions that were previously developed for diverse reactor plant types. The proposed activity will advance such codes by integrating and validating existing capabilities, and extending them for analysis of other reactor types.

The uncertainties in nuclear data for higher actinides are rather large and they impact predictions of isotopic inventories, decay heat, and radiation emission characteristics. Data requiring additional assessments include energy release per fission, spontaneous fission model parameters, fission product yields, half-lives, decay energies, decay branching ratios, and radiotoxicity factors. Improved data need to be incorporated into inventory tracking tools to ensure that they give accurate results.

The recent and continuing growth in computer power motivate the assessment and further development of Monte Carlo-based analysis capabilities applicable to multiple reactor types. Enhancement of these codes would also be investigated, including the propagation of errors as a function of depletion, provision of temperature interpolation capability, and modeling of thermal-hydraulic feedback.

An integrated neutronic and depletion capability is needed for modeling non-equilibrium and equilibrium cycle operations of Generation IV systems, with representation of both their in-core and ex-core fuel cycle segments. Accurate modeling of systems with significant spectral gradients and changes of spectrum with depletion is a key requirement. The tool would employ advanced modules suitable for analysis of different Generation IV systems.

Uncertainties in reactor physics data lead to uncertainties in predictions of depletion-dependent system characteristics. By using sensitivity analysis methods, it is possible to avoid explicit recalculation of the effects for each data variation and at the same time to obtain information on additional data needs. This activity will develop an analytical tool for burnup dependent sensitivity evaluation and models for evaluating the uncertainties in predicted performance characteristics for different Generation IV designs.

### ***Development and Application of Evaluation Methodologies***

This task addresses the need for periodic evaluations of system performance against the Generation IV technology goals. Methodologies for conducting these evaluations will be developed by evaluation methodology working groups comprised of experts from industry, universities, and national laboratories. Participation of international experts will be arranged through the GIF. Because of the strong need to improve evaluation capabilities in the areas of economics and proliferation resistance and physical protection (PR&PP), the working groups for these areas were initiated in FY 2003. Additional working groups may be formed to implement desired improvements in methodologies for evaluating system performance in the

areas of sustainability, reliability, and safety.

An integrated nuclear energy economics model is central to standardized and credible economic evaluation of Generation IV nuclear energy systems. The innovative nuclear systems considered within Generation IV require new tools for their economic assessment, since their characteristics differ significantly from those of current Generation II & III nuclear power plants. In addition, the current economic models were not designed to compare nuclear energy systems featuring new fuel cycle and energy conversion technologies, or to evaluate economics of deployment in different countries or world regions. The *Economics Modeling Working Group* is charged with developing an integrated economics model applicable to the comprehensive evaluation of the economic performance of Generation IV nuclear energy systems.

Methodologies currently available for evaluating proliferation resistance and physical protection (PR&PP) of nuclear energy systems are limited by the lack of accepted figures of merit that provide a sufficient representation of system performance in these areas. A *PR&PP Methodology Working Group* has been formed to develop an improved methodology for assessing Generation IV systems. This group is charged with developing a systematic method for evaluating and comparing the proliferation resistance and physical protection of these systems, including their fuel cycle facilities and operations. To the maximum extent possible, a quantitative and standardized methodology is targeted, as is the ability to identify system features that contribute to the overall resulting assessment of the comparative PR&PP of the system.

The evaluation methodology working groups will focus primarily on developing, testing and verifying the required methodologies, but are also expected to contribute to the application of the methodologies to Generation IV systems. Results of the application studies will be used for periodic re-assessment of system potential and for guiding R&D priorities.

### ***Ten Year Plan***

The high-level ten-year objectives of the Generation IV design and evaluation methods R&D activities are to:

- Enable cost-effective development of high-performance Generation IV systems through coordination and oversight of design related R&D.
- Provide crosscutting capabilities for system design development, safety enhancement, and performance optimization.
- Provide methodologies for measuring the performance of Generation IV systems against Generation IV technology goals.
- Support R&D prioritization based on results of system design analyses and performance evaluations.
- Form the groundwork for licensing the chosen high-performance Generation IV systems via the regulatory process in place when the system development is completed.

The major tasks are supported by funding as shown below in Table 5.7.1.

**Table 5.7.1** Summary of Design and Evaluation Methods Funding Requirements through FY 2013 (\$K)

<b>Task</b>	<b>FY04</b>	<b>FY05</b>	<b>FY06</b>	<b>FY07</b>	<b>FY08</b>	<b>FY09</b>	<b>FY10</b>	<b>FY11</b>	<b>FY12</b>	<b>FY13</b>	<b>Total</b>
Coordination of Design and Evaluation R&D	100	100	200	200	200	200	200	200	200	200	1800
Development of Crosscutting Design and Safety Analysis Capabilities	495	400	1200	2200	3000	3200	3500	3500	3000	2200	22965
Development and Application of Evaluation Methodologies	605	500	800	800	1100	600	600	600	600	600	6805
<b>TOTAL</b>	<b>1200</b>	<b>1000</b>	<b>2200</b>	<b>3200</b>	<b>4300</b>	<b>4000</b>	<b>4300</b>	<b>4300</b>	<b>3800</b>	<b>3000</b>	<b>31300</b>

## ***Major Milestones***

- FY04:** 1. Complete report on specifications for an integrated nuclear economics model.  
2. Complete draft report on PRPP proposed assessment methodology.
- FY05:** 1. Identify and report on required integral experiments to meet nuclear data and neutronic analysis validation needs.  
2. Document benchmark tests to support verification and validation of system dynamics and CFD analysis tools.
- FY06:** 1. Issue draft plan for verification and validation of design and safety analysis software.  
2. Release PR&PP evaluation methodology.
- FY07:** 1. Issue integrated economic evaluation model.
- FY08:** 1. Apply economics methodology to evaluations of Generation IV systems.  
2. Apply PR&PP methodology to evaluations of Generation IV systems.
- FY09-10:** 1. Perform verification and validation tests for neutronic design and fuel cycle modeling tools.  
2. Perform verification and validation tests for system dynamics modeling tools.
- FY11-13:** 1. Report on software verification and validation tests.  
2. Document evaluation methodologies and results of their application testing.

## **5.8 Materials Crosscut**

An integrated R&D program will be conducted to study, quantify, and in some cases, develop materials with required properties for the Gen IV advanced reactor systems. The goal of the National Materials Crosscut Program (NMCP) is to ensure that the required Gen IV materials R&D will be a comprehensive and integrated effort to identify and provide the materials data and its interpretation needed for the design and construction of the selected advanced reactor concepts.

For the range of service conditions expected in Gen IV systems, including possible accident scenarios, sufficient data must be developed to demonstrate that the candidate materials meet the following design objectives:

- acceptable dimensional stability including void swelling, thermal creep, irradiation creep, stress relaxation, and growth;
- acceptable strength, ductility, and toughness;
- acceptable resistance to creep rupture, fatigue cracking, creep-fatigue interactions, and helium embrittlement; and
- acceptable chemical compatibility and corrosion resistance (including stress corrosion cracking and irradiation-assisted stress corrosion cracking) in the presence of coolants and process fluids.

Additionally, it will be necessary to develop validated models of microstructure-property relationships to enable predictions of long-term materials behavior to be made with confidence

and to develop high-temperature materials design methodology for materials, use, codification, and regulatory acceptance.

To make efficient use of program resources, the development of the required databases and methods for their application must incorporate both the extensive results from historic and ongoing programs in the United States and abroad that address related materials needs. These would include, but not be limited to, DOE, NRC, and industry programs on liquid-metal-, gas-, and light-water-cooled reactor, fossil-energy, and fusion materials research programs, as well as similar foreign efforts.

Since many of the challenges and potential solutions will be shared by more than one reactor concept, it will be necessary to work with the system integration managers (SIMs) for each individual reactor concept to examine the range of requirements for its major components to ascertain what the materials challenges and solutions to those will be and then establish an appropriate breakdown of responsibilities for the widely varying materials needs within the Gen IV Initiative. It is expected that there will be two primary categories for materials research needs:

- Materials needs that crosscut two or more specific reactor system and
- Materials needs specific to one particular reactor concept or energy conversion technology.

Where there are commonly identified materials needs for more than one system, it will be appropriate to establish a crosscutting technology development activity to address those issues. Where a specific reactor concept has unique materials challenges, it will be appropriate to address those activities in conjunction with that particular reactor systems's R&D. Examples of this category of materials needs include reactor-specific materials compatibility issues associated with a particular coolant and materials used within only one reactor concept (i.e., graphite within the VHTR).

The National Materials Program within the Gen IV Initiative will have responsibility for establishing and executing an integrated plan that addresses cross-cutting, reactor-specific, and energy-conversion materials research needs in a coordinated and prioritized manner.

Four interrelated areas of materials R&D are generally considered crosscutting: (1) qualification of materials for service within the vessel and core of the reactors that must withstand radiation-induced challenges; (2) qualification of materials for service in the balance of plant that must withstand high-temperature challenges; (3) the development of validated models for predicting long-term, physically based microstructure-property relationships for the high-temperatures, extended-operation periods, and high irradiation doses that will exist in Gen IV reactors; and (4) the development of an adequate high-temperature-materials design methodology to provide a basis for design, use, and codification of materials under combined time-independent and time-dependent loadings.

Reactor-specific materials research that has been identified for the individual reactor and energy-conversion concepts includes materials compatibility with a particular coolant or heat-transfer medium, as well as materials expected to be used only within a single reactor or energy conversion system, such as graphite, selectively permeable membranes, catalysts, etc. A special category of reactor-specific materials research will also include research that must be performed at a pace that

would significantly precede normal cross-cutting research in the same area (e.g. NGNP reactor system materials R&D).

While the current plan addresses materials issues for all the reactors currently being examined within the Gen IV program, there is recognition that the plans to build a VHTR as the Next Generation Nuclear Plant (NGNP) by 2017 will strongly drive much of the materials research during the next ten years of the program. Accordingly, though the four crosscutting activities described below will include materials of interest to all the reactors, where possible, the emphasis will be on materials that meet the needs of the NGNP, while at the same time supporting the other reactor concepts. Where the NGNP materials needs clearly outstrip those of the other reactor systems, they will be addressed independently and the other reactor systems will be able to utilize those results that are relevant.

A final category of materials R&D that is recognized within the Gen IV Program is that which overlaps the materials needs for the development of fuels and reprocessing technology within the Advanced Fuel Cycle Initiative (AFCI) and for chemical processing equipment for the Nuclear Hydrogen Initiative (NHI). While both AFCI and NHI are independent programs with their own research objectives and funding, it has already been recognized their applications will contain many of the same conditions that exist for reactor systems and their components in the Gen IV Program and, hence, may utilize a common set of structural materials. A special involvement among all three programs is being developed and maintained to help ensure that the materials R&D being conducted within them is coordinated to minimize duplication and costs and maximize mutually beneficial materials technology development and qualification.

### ***Ten-Year Plan***

The high-level objectives for the Gen IV Reactor Materials Program are:

- Complete establishment of initial database for candidate materials for high-temperature and radiation service for all Gen IV reactor systems (9/05)
- Complete initial assessment of candidate graphites for irradiation service in the NGNP reactor (9/07)
- Complete preliminary assessment of candidate materials for high-temperature and radiation service for all Gen IV reactor systems and issue recommendations for final qualification (9/08)
- Complete recommended revised simplified methods for satisfying strain limits and creep-fatigue criteria in high-temperature structural design. (9/09)
- Complete development of materials design data needed to order major NGNP components. (9/09)
- Prepare final report on micromechanical models used to predict relationship between microstructure and mechanical properties in structural materials for use in Gen-IV reactor program (9/12)
- Resolve identified shortcomings, issues, and regulatory concerns in high-temperature structural design methodology (9/13)

Table 5.8.1 shows the estimated budget requirements for the ten-year period beginning in FY-04.

**Table 5.8.1** Summary of Required Funding for Crosscutting Materials Tasks for FY 2004 through FY 2013 (K\$).

Task	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	Total
Materials for Radiation Service	280	1400	1850	1850	4900	6000	5000	5000	4000	4000	34280
Materials for High-Temperature Service	75	750	1300	1400	3950	4950	3950	2500	2500	2500	23875
Microstructural Modeling	41	450	800	1500	1900	2100	2100	2000	1800	1500	14191
High-Temperature Design Methodology <sup>15</sup>	296	1000	1500	1500	1500	1500	1500	1500	1500	1500	13296
Reactor-Specific Materials <sup>16</sup>	92	100	100	150	150	150	150	150	150	150	1342
Materials for Energy Conversion <sup>16</sup>	19	30	50	50	50	50	50	50	50	50	449
National Materials Program Management	347	500	600	600	730	730	730	730	730	730	6427
<b>TOTAL</b>	<b>1150</b>	<b>4230</b>	<b>6200</b>	<b>7050</b>	<b>13180</b>	<b>15480</b>	<b>13480</b>	<b>11930</b>	<b>10730</b>	<b>10430</b>	<b>93860</b>

### **Major Milestones**

The projected major milestones for the integrated Gen IV materials program are:

- FY04:** 1. Initiate compilation of database on Gen IV materials  
2. Prepare detailed plans for high-temperature materials experiments  
3. Complete irradiation of preliminary HFIR rabbits capsules and archive samples of NGNP candidate graphites  
4. Issue revised NGNP Materials Qualification and Selection Program Plan
- FY05:** 1. Complete establishment of initial database for candidate materials for high-temperature and radiation service for all Gen IV reactor systems  
2. Complete post irradiation examination of NGNP candidate graphite from HFIR rabbit capsules
- FY06:** 1. Complete design of facilities for both low flux and high flux irradiations  
2. Complete preliminary irradiations and PIE of potential candidate alloys in high flux experiments for NGNP  
3. Select primary high-temperature materials and complete planning needed to qualify alternate materials for NGNP structural components.

<sup>15</sup> Detailed required materials database development to be provided under Materials for High-Temperature Service task

<sup>16</sup> Primary funding for reactor-specific and energy-conversion materials research in specific reactor and NTD budgets, only coordination funding included here in materials crosscutting

- FY07:** 1. Complete selection of primary RPV candidate materials based on screening irradiation experiments.  
 2. Complete graphite physical and mechanical properties evaluations for NGNP  
 3. Complete preliminary irradiation effects studies of NGNP graphites  
 4. Complete preliminary evaluations of materials compatibility for NGNP applications
- FY08:** 1. Complete plan and initiate research to ensure the integrity of NGNP components for a design life beyond 300,000 hours.  
 2. Prepare updated, status report on qualification of crosscutting candidate materials for high-temperature and radiation service in Gen IV reactor systems
- FY09:** 1. Prepare report on results of comprehensive modeling of radiation-induced microstructural evolution in the primary Gen-IV candidate structural materials, identify areas for further model development.  
 2. Complete PIE of preliminary candidate RPV alloys and prepare report on results for NGNP  
 3. Complete development of materials design data needed to order major NGNP components.
- FY10:** 1. Complete irradiation experiments of RPV and insulation materials and complete report on recommendations for application of selected materials for VHTR radiation service  
 2. Complete irradiation creep studies of NGNP graphites
- FY11:** 1. Prepare final report on results of microstructural analysis of irradiated and thermally-aged Gen-IV candidate structural materials.  
 2. Validate final simplified design rules for ratcheting and creep-fatigue damage for Gen IV materials.  
 3. Complete confirmatory irradiations and PIE of RPV alloys for NGNP
- FY12:** 1. Prepare high-temperature materials supporting documents for Gen IV reactor licensing.  
 2. Develop and prepare report on recommendations for RPV surveillance program for NGNP
- FY13:** 1. Prepare final report on integrated models for assessing radiation-induced and time-dependent, high-temperature changes in Gen-IV structural materials and provide recommendations for any further studies required to refine and validate the models in support of Gen-IV reactor operations.  
 2. Complete final reports on mechanical property, microstructural and corrosion evaluations of irradiated prime candidate materials in conventional post-test and in-situ SC water environments for SCWR.

## **5.9 Energy Conversion Crosscut**

Generation IV energy conversion R&D focuses on the identification and development of energy conversion technologies that support implementation of Generation IV reactor systems, either through improved efficiency, reduced costs or enabling new energy products. Energy conversion technologies that optimally couple to the performance characteristics of Generation IV reactors will result in more efficient and cost effective nuclear power systems.

The Energy Conversion program R&D activities address advanced electrical conversion technologies that could potentially result in lower electricity costs from Generation IV plants. Initial activities will focus on high temperature Brayton cycles including very high temperature helium cycles and supercritical carbon dioxide cycles.

The advanced electrical conversion research will include:

- High temperature Helium Brayton Cycles: Systems studies and scaled demonstration experiments will be performed to investigate direct and indirect cycle control issues, multi-reheat and interstage cooling costs and performance benefits, and high temperature interface issues. This effort will be closely coordinated with the materials crosscut and the VHTR design efforts.
- Supercritical Carbon Dioxide Brayton Cycles: These feasibility and technology development studies will establish a baseline supercritical CO<sub>2</sub> Brayton design for coupling to Generation IV systems. This effort will identify the materials, technology, and systems issues and requirements, and initiate key technology development efforts including potential improvements in turbomachinery design, fabrication, or construction techniques. Cost implications of design approaches that maximize performance will be assessed and viability demonstrations will be performed.

### ***Ten-Year Plan:***

During the FY04 through FY13 period the Generation IV Energy Conversion technology area will establish requirements, complete technology assessments, perform key technology development efforts, and initiate laboratory or pilot plant level demonstrations necessary to support technology selections. Table 5.9.1 shows required funding levels.

The Energy Conversion program will focus on the conversion technologies and operational conditions that are considered highest priority for Generation IV system applications, and implement R&D to support those applications. Additionally, to further the goals of the program, collaborations where appropriate will be developed with DOE-EE, other government agencies, other nations, universities, and industry to leverage relevant research.

**Table 5.9.1.** Energy Conversion Required Budget FY 2004- FY 2013

	FY04 <sup>17</sup>	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	Total
<b>TOTAL</b>	<b>600</b>	<b>5000</b>	<b>5000</b>	<b>5000</b>	<b>6000</b>	<b>6000</b>	<b>7000</b>	<b>8000</b>	<b>8000</b>	<b>8000</b>	<b>58600</b>

### ***Major Milestones:***

**FY04:** 1. Complete conceptual designs for advanced helium Brayton cycles incorporating interstage reheat and cooling features. Perform preliminary cost studies to assess cost – benefit of advanced designs.

2. Complete conceptual design for a nominal 300 MWe Gen IV supercritical CO<sub>2</sub> system for intermediate temperature Gen IV systems

3. Complete initial assessment of supercritical CO<sub>2</sub> plant costs

**FY05:** 1. Develop final design and initiate fabrication activities for SC CO<sub>2</sub> lab scale demonstration experiment.

2. Develop final design for electrically heated Brayton cycle demonstration experiment.

<sup>17</sup> FY04 funding includes \$470K for Program Coordination, \$20K for Advanced Electrical Conversion, and \$110K for SC CO<sub>2</sub> Turbomachinery

3. Complete final design and construct selected IHX for scaling demonstration experiments
- FY06:** 1. Construct electrically heated SC CO<sub>2</sub> demonstration experiments.  
2. Perform IHX component tests to support demonstration tests.
- FY07:** 1. Construct electrically heated He Brayton cycle demonstration experiments.  
2. Complete report on technical basis for advanced electrical conversion options for Gen IV systems.
- FY08:** 1. Design of improved SC CO<sub>2</sub> turbine and compressor designs for next stage.
- FY09:** 1. Complete construction of advanced design components for SC CO<sub>2</sub> system and initiate testing.
- FY10:** 1. Initiate design and fabrication of alternative He Brayton components.  
2. Design pilot scale SC CO<sub>2</sub> demonstration.
- FY11:** 1. Construct pilot scale components for SC CO<sub>2</sub> system.  
2. Fabricate alternative components and initiate tests for lab scale He Brayton cycle.
- FY12:** 1. Complete construction of pilot scale demonstration components for SC CO<sub>2</sub> system.  
2. Complete lab scale He Brayton demo with alternative components and initiate testing.
- FY13:** 1. Initiate pilot scale SC CO<sub>2</sub> demonstration experiments.  
2. Complete final design for pilot scale He Brayton cycle components and demonstration tests.

## 6 SUMMARY

The total costs for concept and crosscut R&D are summarized in Tables 6.1 and 6.2. Table 6.1 shows the total required costs for FY2004 to FY2013.

**Table 6.1** Total Required Costs for FY2004 to FY2013 (\$M).

	<b>FY04</b>	<b>FY05</b>	<b>FY06</b>	<b>FY07</b>	<b>FY08</b>	<b>FY09</b>	<b>FY10</b>	<b>FY11</b>	<b>FY12</b>	<b>FY13</b>	<b>TOTAL</b>
2.0 NGNP	19.90	68.40	122.10	139.90	149.80	171.50	161.00	147.10	163.50	167.70	1310.9
3.0 SCWR	0.90	0.80	3.78	4.87	7.76	7.90	9.30	8.79	7.30	4.98	56.38
4.0 GFR	0.40	0.50	5.50	5.50	6.00	6.00	5.90	-	-	-	29.80
5.0 LFR	1.00	0.80	5.50	5.50	6.00	6.00	5.20	-	-	-	30.00
6.0 SFR	0.04	2.54	5.50	5.00	6.50	6.50	2.50	5.00	5.00	5.00	43.58
7.0 MSR	0.04	0.16	3.20	4.30	4.50	4.50	4.00	4.00	6.00	6.00	36.70
8.0 D&EM	1.20	1.00	2.20	3.20	4.30	4.00	4.30	4.30	3.80	3.00	31.30
9.0 Materials	1.15	4.23	6.20	7.05	13.18	15.48	13.48	11.93	10.73	10.43	93.86
10.0 Energy Conversion	0.60	5.00	5.00	5.00	6.00	6.00	7.0	8.00	8.00	8.00	58.60

**Table 6.2** FY 2004 Generation IV R&D Funding at Level 3 by Performer \$(K).

WBS Number	FY04										Total	
	ANL	BNL	INEEL	LANL	LLNL	ORNL	SNL	AL	ID	Univ		HQ
1.01 <b>Technical Integration</b>	40		580									620.0
1.01.01 Tech Integration Support			355									
1.01.02 GIF Activities	40		225									
1.01.03 Systems Analysis												
1.02 <b>NGNP</b>	200		2,770			525			4,800	250	406	14,950.0
1.02.01 SD&E +NGNP SBIR			125						4,800	250	406	8,250.0
1.02.02 Materials			425			275						700.0
1.02.03 Energy Conversion												
1.02.04 Fuels												6,000.0
1.02.05 Project Mgt & Support			1,041									
1.02.06 Indep. Techn. Review			650									
1.02.07 Preconceptual Studies	200		529			250						
1.03 <b>SCWR</b>	100		550			100			150			900.0
1.03.01 SD&E	100		270						150			
1.03.02 Materials			280			100						
1.03.03 Energy Conversion												
1.04 <b>GFR</b>	200		200									400.0
1.04.01 SD&E	80		150									
1.04.02 Materials												
1.04.03 Energy Conversion												
1.04.04 Fuels	120		50									
1.05 <b>LFR</b>	227			227	227						319	1,000.0
1.05.01 SD&E	203				167						319	
1.05.02 Materials	24			227	60							
1.05.03 Energy Conversion												
1.06 <b>SFR</b>	40											40.0
1.06.01 SD&E	40											
1.06.02 Materials												
1.06.03 Energy Conversion												
1.07 <b>MSR</b>						40						40.0
1.07.01 SD&E						40						
1.07.02 Materials												
1.07.03 Energy Conversion												
1.08 <b>Design &amp; Evaluation Methods</b>	570	150	125			75			280			1,200.0
1.08.01 Program Coordination	100											

WBS Number	FY04											Total
	ANL	BNL	INEEL	LANL	LLNL	ORNL	SNL	AL	ID	Univ	HQ	
1.08.02 Model Improvement	370		125									
1.08.03 Economics						75			180			
1.08.04 PRPP	100	150							100			
<b>1.09 Materials</b>						1,150						1,150.0
1.09.01 Program Coordination						347						
1.09.02 Radiation Service						280						
1.09.03 High-Temp Service						75						
1.09.04 Microstruct Modeling						41						
1.09.05 HT Design Methodology						296						
1.09.06 Reactor-Specific						92						
1.09.07 Energy Conversion						19						
<b>1.10 Energy Conversion</b>							600					600.0
1.10.01 Program Coordination							60					
1.10.02 Adv Electrical Conv							370					
1.10.03 SC CO2 Turbomach							170					
<b>1.11 Program</b>								200		1,400	1,500	3,100.0
1.11.01 R&D SBIR 2.85%											244	244.0
1.11.02 Program Control								200				200.0
1.11.03 Program Reserve										1,400	409	1,809.0
1.11.04 Budget Reductions											847	847.0
<b>TOTAL</b>	1,377	150	4,225	227	227	1,890	600	200	5,230	1,650	2,225	24,000